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EVALUATION OF SAXTON CORE III
FUEL MATERIALS PERFORMANCE

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W. R. Smalley

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APPROVED: E. Roberts

E. Roberts, Manager Irradiation Planning

APPROVED: R. N. McDaniel
R. N. McDaniel, Projects Manager
NFD Projects

APPROVED: R. C. Goodspeed
R. C. Goodspeed,
Manager
NFD Field Projects

*Patent Cleared
4/23/74*

WESTINGHOUSE ELECTRIC CORPORATION
Nuclear Energy Systems
Pittsburgh, Pennsylvania 15230

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Attention: Chief, Water Reactors Branch

Battelle Northwest Laboratory (1)
P. O. Box 999
Richland, Washington 99352
Attention: Mr. M. D. Freshley

U. S. Atomic Energy Commission (1)
Directorate of Licensing
Washington, D. C. 20545
Attention: L. S. Rubenstein

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R. C. Goodspeed
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E. Roberts
J. B. Roll

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J. T. Barnes
J. A. Corbett
D. D. Durigon
D. T. Galm
R. C. Goodspeed
N. R. Metcalf
E. S. Schwartz
W. S. Winnowski

Staff of Battelle Memorial Institute Hot Laboratory, (V. G. Scotti, Chief)

Reduction and Evaluation of Data

M. G. Balfour	G. Hopkins	G. W. Parry
R. F. Boyle	A. C. Hott	C. S. Rim
H. H. Caldwell	E. Iwinski	R. L. Stover
T. E. Caye	P. J. Kuchirka	
S. B. Dalgaard	P. M. Maxin	
J. R. Guthridge	J. B. Melehan	

Preparation, Typing and Editing of Report

T. E. Caye

S. Cerni

H. H. Crain

M. A. DeMarco

R. C. Goodspeed

K. R. Jordan

R. S. Miller

J. L. Popovich

E. Roberts

J. B. Roll

ABSTRACT

Approximately 250 mixed oxide (PuO_2 - UO_2) fuel rods from Saxton Core II were reconstituted into seven new loose lattice assemblies and irradiated in Core III to peak burnups of up to 51,000 MWD/MTM. A sampling of these rods, representing a wide range of peak power levels and burnups, were subjected to hot cell examinations, including visual inspection, gamma scanning, profilometry, length measurement, collection and analysis of released fission product gases, metallography, burnup analysis, clad hydrogen analysis and mechanical testing of cladding specimens. One rod was removed at an interim shutdown in 1970 after 1720 EFPH in Core III; seven rods were removed at the mid-life shutdown (3720 EFPH); and eight rods were removed at end-of-life (5940 EFPH).

These examinations showed that the overall performance of the PuO_2 - UO_2 fuel was satisfactory. The fuel rods exhibited progressive changes in dimensions, fission gas release, oxidation of the cladding, fuel microstructure, and mechanical properties which were consistent with increasing burnup and higher power operation in Core III. Generally, these changes had no apparent adverse effects on the performance of the mixed oxide fuel. Defects which developed in certain high power rods between Core III mid-life and end-of-life did not appear to be related to any burnup, power or other inherent performance limit of mixed oxide fuel.

SECTION 1

INTRODUCTION

1-1. DESCRIPTION AND OBJECTIVES OF SAXTON PLUTONIUM PROGRAM

The Saxton Plutonium Project is part of an overall program to advance plutonium recycle technology in water reactor systems. It has been conducted by the Westinghouse Electric Corporation in co-operation with the Saxton Nuclear Experimental Corporation (SNEC) under USAEC Contract No. AT (11-1)-3044, previously AT (30-1)-3385. The contract is now administered by the USAEC Chicago Operations Office, but earlier by the New York Operations Office, for the Joint United States-Euratom Research and Development Board.

The project has been an integrated recycle program which included design, fabrication, reactor operation, and post-irradiation evaluation of a partial plutonium core. Irradiation was performed in the Saxton reactor, which was well suited to commercial bulk engineering tests because it was highly instrumented, and core performance could be continuously evaluated.

The overall purpose of the Saxton Plutonium Project was to develop information concerning the utilization of plutonium enriched fuel in pressurized water reactor (PWR) systems.

More specifically the objectives were to:

- a. Perform pilot-scale tests of plutonium enriched fuel in a water reactor environment.
- b. Compare the performance of mixed oxide fuel fabricated by two economically promising techniques, i.e., pelletizing vs. vibrationally compacting (vipac).
- c. Obtain nuclear data of interest to plutonium recycling, especially with regard to depletion and generation of transuranic isotopes.
- d. Provide a preliminary basis for the selection and design of plutonium fuel for a large PWR.

These objectives were related primarily to Saxton Core II operations and were addressed in a series of progress reports ^[1] and final reports ^[2,3].

The project was initiated in early 1964, and core design and fabrication activities were completed with delivery of the first plutonium assemblies at the reactor site in October 1965. Loading of Saxton Core II and initial operation with the mixed oxide fuel were accomplished by December 1965. Core II operations continued until October 18, 1968.

The successful performance of the plutonium fuel in Core II led eventually to the Saxton "Extended Burnup Test". In this phase of the program some 250 rods were selected from the Pu region of Saxton Core II and reconstituted into new "loose lattice"* assemblies for further irradiation to high burnups as part of Core III.^[3] The objectives of the Extended Burnup Test (also called the "Loose Lattice" program) were to:

- a. Demonstrate performance capability of Zircaloy-clad mixed oxide fuel elements over a broad spectrum of burnups and power levels.
- b. Obtain depletion characteristics and transuranic isotope generation data for high burnup, mixed-oxide fuel.

1-2. SCOPE OF REPORT

This report is primarily concerned with the first of the above two objectives. Specifically, it covers the materials evaluation of the mixed oxide fuel irradiated in the loose lattice region of Saxton Core III. The fuel rods evaluated include the following:

- a. One rod removed from the center 3 x 3 subassembly during the interim shutdown in mid-1970, after 1720 effective full power hours (EFPH) in Core III.
- b. Seven rods removed from three loose lattice assemblies at the mid-life shutdown in 1971, after 3720 EFPH in Core III.
- c. Eight rods removed from various loose lattice assemblies at end of life (May 1972), after 5940 EFPH in Core III.

* So-called because plutonium fuel rods were installed at a wider pitch, which resulted in a higher water-to-fuel ratio and a corresponding increase in system reactivity without adding fresh fuel.

The nuclear design, rod selection and fabrication of the loose lattice fuel assemblies are discussed in detail in other reports.^[1,3] Additional background information and results of examinations of extended burnup fuel are given in progress reports^[1] covering the last three years of the program. All work related to isotopic depletions and comparison of predicted and measured burnups in Core III is outside the scope of this report and is covered in reference 4.

SECTION 2

OPERATING HISTORY OF SAXTON CORE III

The initial power operation of Core III occurred on December 11, 1969. Reactor power was increased from 11 Mwt to 19 Mwt on December 15 and, except for several brief periods, remained at 19 Mwt until January 9, 1970, when nearly full reactor power (22.6 Mwt) was achieved. During this early operating period, at-power physics tests were initiated. They were performed at several different power levels and provided the nuclear basis for further operation of Core III. In addition, three cycles of load follow operation were completed in January to obtain nuclear data on axial xenon variation. Late in January the reactor was shut down for maintenance and repairs of plant components.

On February 11, load follow operation resumed and continued until February 26, when problems with the flux mapping system necessitated a hot shutdown for repairs. After repair of the system, the reactor was returned to full power on March 2. It operated until March 9, when an unscheduled scram necessitated another shutdown. After a one-month shutdown for repairs, maintenance, and training, the reactor was returned to power on April 9 and operated at full power with load follow cycling until April 17. It was then shut down for six days for further maintenance. From April 23 until the planned interim shutdown on May 14, the reactor was at 22.6 Mwt with load cycling between full power and 40 percent power.

The reactor was shut down from May 14 until August 24, 1970 for the examination of fuel rods from removable assemblies. It was started up on August 24 and returned to full power on August 28. Except for a three-day shutdown for repair of a flux thimble drive, the reactor operated at full power until the planned September 18 shutdown. During this period, flux map data were analyzed to provide relative assembly and rod powers.

During the last three months of 1970, the reactor was operated for 43 days (mostly at ~23 Mwt) and shut down the remainder of the period for operator training and maintenance. In the first quarter of 1971, it operated at power for 34 days, about half of which was at full reactor power of 23.5 Mwt. Most of the down time was for loading of special, short-term irradiation test assemblies into the reactor. On March 12, the mid-life (MOL) shutdown was initiated.

The Saxton reactor remained shut down from March to November 1971 for fuel examinations, interchange of fuel, system modification and maintenance. On November 18, the reactor was started and at-power physics testing began. The power was increased from 9 Mwt to 20 Mwt on November 22, and then further increased to ~23 Mwt on December 1. With the completion of at-power physics tests on December 6, the reactor was shut down for three days. It was returned to power on December 9 and operated at or near full power for essentially the remainder of the month. The first load follow operations since the MOL shutdown were also achieved in December.

The reactor operated at the highest power levels achieved in Core III (24.4 to 25.0 Mwt) with load follow cycling during the first 14 days of January 1972. It was shut down for planned maintenance from January 14 until January 31, but was taken to full power on February 1 and operated in the load cycle mode until an unscheduled shutdown on February 12, 1972. This shutdown was necessitated by high primary coolant activity and the plant's limited gaseous and liquid waste handling capability. At no time was the Technical Specification exceeded. It was inferred from the activity level that a significant number of fuel rods had developed defects.

After a 17-day shutdown, the reactor was started up on February 29 and operated throughout March and April without load cycling and at reduced power levels (generally between 15 and 16.5 Mwt). These revisions to the operating mode were invoked to minimize further increases in coolant activity. The final power operation of Saxton Core III was at 15 Mwt on May 1, 1972, when the reactor was shut down. As of the final shutdown, the energy generated in Core III was 5819 MWD, equivalent to a core average burnup of 8082 MWD/MTM and a peak pellet burnup of ~51,000 MWD/MTM. A summary of the peak powers, burnup,

load cycles, etc. for the lead loose lattice fuel rods throughout Core III is given in Table 2-1.

A tabular summary of Core III reactor power history by major time intervals is shown in Table 2-2; a graphical summary as a function of calendar time is presented in Figure 2-1.

TABLE 2-1

SUMMARY OF OPERATING PARAMETERS FOR LEAD RODS IN SAXTON CORE III

	Through May 1970 Shutdown	Through MOL Shutdown (Mar. 1971)	Through EOL (May 1, 1972)
Cumulative Energy Generated, MWD	1,685	3,637	5,819
No. of Load Cycles	138	464	631
Peak Linear Power, Kw/ft ^(a)			
1. Peak Power Rod (BOL → EOL) ^(b)	21.2	18.4	18.0
2. Peak Power Rod (MOL → EOL) ^(c)	-	-	21.2
3. Peak Burnup Rod (in 3 x 3)	16.7	16.7	14.3
4. Peak Burnup Rod outside 3 x 3	9.8	13.0	12.2
Cumulative Peak Pellet Burnup, MWD/MTM ^(d)			
1. Peak Power Rod (BOL → EOL) ^(b)	25,300	32,900	45,200
2. Peak Power Rod (MOL → EOL) ^(c)	-	-	29,100
3. Peak Burnup Rod (in 3 x 3)	35,200	41,900	51,000
4. Peak Burnup Rod outside 3 x 3	32,300	36,400	47,100

(a) Best estimate, thermal basis (thermal = 0.974 fission) during interval prior to shutdown date indicated.

(b) In Core III from beginning of life to end of life.

(c) Inserted at MOL Shutdown.

(d) Best estimate, fission basis.

TABLE 2-2

SAXTON CORE III

REACTOR POWER HISTORY

Time Interval	Number of Days	Average MWT
12/12/69 to 1/20/70	40	16.3
1/21/70 to 2/10/70	21	0
2/11/70 to 2/26/70	15	18.3
2/27/70 to 3/01/70	3	0
3/02/70 to 3/09/70	7	19.7
3/10/70 to 4/08/70	29	0
4/09/70 to 4/17/70	8	21.8
4/18/70 to 4/21/70	3	0
4/22/70 to 5/14/70	22	17.9
5/15/70 to 8/23/70	101	0
8/24/70 to 9/07/70	14	21.3
9/08/70 to 9/09/70	1	0
9/10/70 to 9/18/70	8	16.9
9/19/70 to 10/08/70	20	0
10/09/70 to 11/07/70	29	18.6
11/08/70 to 11/15/70	7	0
11/16/70 to 11/23/70	7	16.5
11/24/70 to 12/20/70	26	0
12/21/70 to 1/28/71	38	19.1
1/21/71 to 1/31/71	3	0
2/01/71 to 2/05/71	4	16.0
2/06/71 to 3/10/71	33	0
3/11/71 to 3/12/71	1	13.5
11/19/71 to 11/21/71	3	8.9
11/22/71 to 11/30/71	9	19.4
12/01/71 to 12/06/71	6	21.8
12/07/71 to 12/09/71	3	0
12/10/71 to 12/20/71	11	22.3
12/21/71 to 12/25/71	5	23.0
12/26/71 to 12/27/71	2	0
12/28/71 to 1/14/72	18	24.0
1/15/72 to 2/01/72	18	0
2/02/72 to 2/11/72	10	23.2
2/12/72 to 2/29/72	18	0
3/01/72 to 3/15/72	15	14.3
3/16/72 to 4/05/72	21	16.1
4/06/72 to 4/12/72	7	15.3
4/13/72 to 5/01/72	19	14.5

Figure 2-1 Schematic Summary of Reactor Power History - Saxton Core III

SECTION 3

POST-IRRADIATION EXAMINATION AND EVALUATION

3-1. ROD RR REMOVED AT INTERIM SHUTDOWN-1970

3-1.1 Irradiation History

The first fuel removed from the loose lattice region was rod RR, which was one of four high burnup rods irradiated in the central removable sub-assembly during the early stages of Core III. This rod was removed from the sub-assembly during the Interim Shutdown in mid-1970 and, after on-site visual and profilometer scanning, was shipped to the Hot Laboratory of the Westinghouse Post-Irradiation Facility (WPIF). Along with the other three rods in the center sub-assembly, rod RR had operated at a peak linear heat rating of ~16 kw/ft early in Core III and had achieved a peak burnup of ~35,000 MWD/MTM. Thus, it was considered representative of the highest burnup mixed oxide fuel in the Saxton core as of mid-1970. It was selected for hot cell examination to provide early data on materials performance of fuel in the Extended Burnup program.

3-1.2 Non-Destructive Examinations

a. Visual Examination

Detailed visual examination of rod RR in the Hot Laboratory revealed that its overall appearance was similar to that of the highest burnup $\text{PuO}_2\text{-UO}_2$ rods removed at the end of Core II. [3] Prior to cleaning, the rod exhibited uniformly light to moderately thick crud over most of its surface. It also showed the usual scratches and score marks, which resulted from removal of the rod from the sub-assembly and from subsequent handling operations.

After cleaning,* the major surface features were patchy areas of non-uniform color over most of the center 24 inches of the rod. These areas were characterized by alternately dark and light zones, both of irregular shape. Generally, the dark areas were non-lustrous while the lighter ones were somewhat shiny. These conditions are illustrated in Figure 3-1.

* Cleaning consisted of thoroughly wiping with a soft cloth soaked with demineralized water.

Another feature was the transition from the patchy condition to a uniform, semi-lustrous black surface in areas enclosed by the second and third grids. A typical area illustrating such a transition is shown in Figure 3-2. The top and bottom 7 inches of the rod appeared to be generally black and uniformly lustrous, except for grid contact marks and handling scratches. The visual examination of rod RR revealed no evidence of swelling, hydride blisters, cracks, or other defects.

b. Gamma Scan

After visual examination, the rod was scanned with a sodium iodide scintillation crystal detector to determine gross gamma activity at quarter-inch intervals. The resulting data are shown in Figure 3-3 and indicate two burnup peaks, one just below and one immediately above the second grid from the bottom end of the rod. Note also that the distribution of gamma activity suggests a power shift early in Core III toward the bottom end of the rod in contrast to a more uniform peaking close to the center for rods scanned at end of Core II. Also evident from the plot is the depression in activity at two of the grid locations: second and third grids, the center lines of which are located at 14.25" and 24.25" from the bottom end of the rod, respectively. The gamma scan data was used in the selection of metallographic and burnup samples.

c. Length Measurements

Length measurements made on rod RR, as shown in the table below, indicate a further increase of only .023 percent as a result of irradiation in Core III, or a total increase of 0.217 percent from its as-fabricated length. This increase is slightly less than the maximum measured length change observed at the end of Core II.[3]

TABLE 3-1

LENGTH CHANGE DATA--ROD RR

<u>As-Fabricated</u> <u>Length,</u> <u>(Inches)</u>	<u>EOC II</u> <u>Length,</u> <u>(Inches)</u>	<u>Final</u> <u>Length,</u> <u>(Inches)</u>	<u>Incremental</u> <u>Increase</u> <u>in Core III</u> <u>(%)</u>	<u>Total</u> <u>Increase</u> <u>(%)</u>
39.083	39.159	39.168	0.023	0.217

d. Profilometry

Rod RR was scanned with an in-cell profilometer to produce a spiral trace. The reduced data showed no anomalous conditions such as blisters, bulges, unusual ovality or significant ridging.

→ TOP OF ROD

MACRO 5326

3.8X

Figure 3-1 Non-Uniform Surface Near Center of Rod RR
After Cleaning

→ TOP OF ROD

MACRO, 5327

3.8X

Figure 3-2 Transition Area at Lower Edge of Third Grid
(Axial Location: 23.8 Inches from Bottom of Rod RR)

Figure 3-3 Rod RR Gamma Scan Data Plot

In addition, mean diameter and ovality were not significantly different than at reconstitution. The data also indicate reduced diameters ("creepdown") of 0.5 to 1.0 mil in the higher power regions as compared to diameters near the ends of the rod. Such diameter reductions are consistent with those observed on the highest burnup rods at end of Core II.^[3] A summary of the profilometer data (showing mean, minimum and maximum diameters at one-inch intervals) is presented in Figure 3-4.

3-1.3. Destructive Examinations

a. Fission Gas Release

The rod was successfully punctured for collection and subsequent analysis of fission product gases. The total gas collected, as determined by pressure change measurements and corrected to STP, was 123.1 cm³. As expected, this volume was significantly higher (by at least 30 percent) than that collected for any pelleted fuel rods at end of Core II^[3], and reflects the higher burnup. The results of the mass spectrometric analysis are given in Table 3-2 and show that about 90 percent of the collected gas was xenon and krypton. (Isotopic data for xenon and krypton are given in Appendix A.) Most of the remaining gas was helium. This composition is essentially the same as for fission gas samples collected from the highest burnup pellet rods at end of Core II. Similarly, the fractional release from rod RR was approximately the same as for peak rods after exposure in Core II^[3] -- about 34 percent.

b. Metallographic Examinations

After copper electroplating certain areas of the rod and sectioning it, representative sections were metallographically examined. The procedures for mounting, grinding, polishing, and etching of metallographic samples are given in Appendix B. The first two sections were examined to determine general structural characteristics of the cladding and fuel, e.g. oxide films on the cladding, fuel-clad interaction and type and extent of fuel grain growth. These sections were transverse planes 12.5 in. and 17.5 in. from the bottom end of the rod and represented peak power locations as indicated by the gamma scan and in-core flux maps. The major features observed were:

1. The oxide film thickness on the outer surface of the cladding was typically 0.8-0.9 mil (Figure 3-5), but varied from 0.4 to 0.9 mil at the 12.5 inch location and from 0.5 to 1.0 mil at the 17.5 inch location. These film thicknesses are slightly greater than the maximum of ~0.8 mil observed on rods at the end of Saxton Core II^[3], but are consistent with increased exposure time at high power.

Figure 3-4 Saxton Fuel Rod RR Profilometry

TABLE 3-2

MASS SPECTROMETRIC ANALYSIS OF FISSION GAS FROM ROD RR

Composition	
Gas	Mole-%
H ₂	0.15
He	8.94
N ₂	0.78
O ₂	0.007
Ar	0.27
Kr	5.99
Xe	83.87

Figure 3-5 Outer Surface Oxide Film on Rod RR

2. The extent of clad hydride precipitation was not significantly greater than in samples examined at end of Core II. Actual hydrogen concentrations obtained by analysis of gases extracted from 1/4" ring sections of cladding as indicated later in this report, confirmed the metallographic results.
3. There was much evidence of inner surface oxidation of the cladding. The thickness of the gray ZrO_2 layer was typically 0.2 to 0.4 mil, similar to that observed on mixed oxide fuel at the end of Core II.^[3]
4. Numerous areas were observed on both samples where the fuel appeared to be bonded to the clad inner oxidized surface. A typical area is shown in Figure 3-6.
5. Consistent with the higher linear power operation achieved in Core III, there was evidence of higher fuel temperatures than in the highest burnup Core II samples. A larger fraction of fuel exhibited equiaxed grain growth and metallic fission product precipitates. In addition, there was some evidence of columnar grains, numerous radially oriented pores, and a collection of large pores near the center of both samples. These conditions are illustrated in Figure 3-7.

Detailed examination of one of the sections (at 17.5") revealed local areas at the inner surface of the clad where apparent grain boundary "attack" had occurred to a depth of about one mil. The other transverse section, at 12.5", did not show this condition. Further transverse (T) and longitudinal (L) sections were examined at 1.8-2.8 inches (L), 15.5-16.5 inches (L), 26.3-27.3 inches (L), 28.3 inches (T), and 36.0-37.6 inches (L, plenum region) from the bottom, respectively. Of these additional sections, only the extreme positions did not show evidence of inner surface reaction zones. The remaining sections, between 15.5 and 28.3 inches from the bottom, all exhibited varying amounts of this phenomenon. The peak heat flux section (12.5 inches) previously examined was reground ~200 mils and was again, free of reaction zones, indicating that there is not a clear correlation with fuel rod power.

A typical I.D. reaction zone is shown in Figure 3-8. The zones were semi-elliptical in shape, and typically extended ~3 mils in length and only ~1 mil in depth, although lengths up to 14 mils and depths up to 3 mils had been observed. The zones typically occurred at several places around the clad circumference, with no consistent pattern. They were characterized by an apparent attack along the grain boundaries, and, in some cases, some of the grains had separated and adhered to the fuel (Figure 3-9). Etching of the specimen in Figure 3-8 revealed a "coring" effect within the grain

906.4

250X

Figure 3-6 Rod RR: Local Bonding of Fuel to Inner Surface of Cladding

EDGE

CENTER

Figure 3-7 Rod RR Fuel Cross Section, Edge to Center, at 12.5" from Bottom of Rod (as-polished)

906 .9

(500X)

Figure 3-8 Clad I.D. Reaction Zone Etched with Chromic Acid-Oxalic Acid

910.3

AS-POLISHED (500X)

Figure 3-9 I. D. Reaction Zone Showing Pullout of Clad Grains

boundaries. The intergranular nature of the attack was confirmed by polarized light metallography and replication and electron microscopy. None of the observations would indicate this condition was detrimental to fuel rod integrity because of its limited extent.

As indicated previously, incipient columnar grain formation and a collection of large pores were evident on the micrographs of the peak heat flux sections of rod RR. A beta-gamma autoradiograph of the 12.5" plane (Figure 3-10) shows a slight annular depleted region about the center, which is characteristic of a section with columnar grain growth. In contrast, the β - γ autoradiograph of the 17.5" plane did not exhibit this condition, probably because it operated at a slightly lower power in Core III than the 12.5" section.

c. Hydrogen Analysis of Cladding Samples

Two 1/4" long ring sections of cladding--one from the 10.9" location and the other from 20.6"--were analyzed by the vacuum hot extraction method for hydrogen. The results were as follows:

<u>Sample Location</u>	<u>H₂ Concentration, ppm</u>			
	<u>Individual Values</u>			<u>Average</u>
10.9"	79	74	66	73
20.6"	97	80	85	87

These values fall within the observed range of values obtained from end of Core II samples^[3] and confirm the metallographic observations of no unusual concentrations of hydrogen in the clad.

d. Burnup Analyses

Two burnup samples from near the peak power positions were analyzed by mass spectrometric techniques for isotopes of uranium and plutonium and to determine the ratios Nd-148/U-238 and Pu-239/U-238. The results are shown in Table 3-3.

The axial burnup shape deduced from the post-irradiation gamma scan was normalized to the Nd-148 data to obtain a best estimate rod average burnup of 25,100 MWD/MTM and a peak pellet burnup of 33,200 MWD/MTM at 17.4 inches from the bottom of the rod.

Figure 3-10 Photomicrograph and β - γ Autoradiograph of Fuel Rod
RR Transverse Section, Peak Heat Flux Zone, 12.5 Inches
from Bottom of Rod

TABLE 3-3

MASS SPECTROMETRIC ANALYSIS ROD RR

	U Atom Percent Abundance				Pu Atom Percent Abundance ^(a)					Atom Ratio	
Sample Location (In. From Bottom of Fuel Rod)	U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Nd-148/ U-238 (x 10 ⁴)	Pu-239/ U-238 (x 10 ²)
11.0-11.5	0.00431	0.486	0.0506	99.459	0.315	61.411	28.084	8.627	1.563	5.943	3.097
18.5-19.0	0.00434	0.476	0.0530	99.467	0.346	60.302	28.673	8.934	1.695	6.062	2.972
Sample Location (Inches From Bottom of Fuel Rod)				Burnup, MWD/MTM.					Percent Difference ^(b)		
				Heavy Isotope					Nd-148		
11.0-11.5				33,690					31,990	+5.3	
18.5-19.0				34,440					32,640	+5.5	

(a) Date of Analysis: December 10, 1970

(b) $\frac{\text{Heavy Isotope} - \text{Nd}}{\text{Nd}} \times 100$

3-1.4 Inferred Performance of Rod RR

The examinations of rod RR provided early evidence of the satisfactory performance of mixed oxide fuel at significantly higher burnups and slightly higher powers than experienced by any fuel in Core II. Rod RR showed good dimensional stability with no evidence of blisters, bulges, unusual ovality or significant ridging. Although the total volume of gas was 30 percent higher, fractional release of fission gases from the rod was approximately the same as for lead rods at end of Core II.

Visual and metallographic examinations revealed no unusual corrosion of the Zircaloy cladding. External oxide films were slightly thicker but consistent with increased exposure time at high power. Hydrogen levels in the cladding were about the same as in end of Core II samples.^[3] There was evidence of more inner surface oxidation and bonding of the fuel to the cladding than seen on lower burnup mixed oxide fuel. Grain growth patterns in the fuel were consistent with slightly higher peak powers in Core III. The only anomalous condition observed was apparent local attack of grain boundaries at the clad inner surface on several samples between the 15" and 28" axial positions. Typically, the penetration was about one mil (0.001"). However, the condition had no apparent adverse effect on the overall performance of the rod.

3.2. RODS REMOVED AT CORE III MID-LIFE SHUTDOWN

3-2.1. Sampling Plan

Seven rods from the loose lattice assemblies were selected for hot cell examination after irradiation through Core III mid-life (MOL), approximately 3720 effective full power hours. These seven rods represented the full spectrum of power history and a variety of rod locations in an assembly, e.g., peripheral or interior. The rod average power and burnup of each rod are summarized in Table 3-4.

With the exception of center 3 x 3 rod LZ, the rods selected were from two loose lattice assemblies: four rods from Assembly 503-17-2 (Core Location D2) and two rods from Assembly 503-17-9 (Core Location E4). The core locations of these assemblies and rods are indicated in Appendix C.

TABLE 3-4

SUMMARY OF ROD AVERAGE POWERS AND BURNUPS
OF FUEL RODS IN MID-LIFE SAMPLING PLAN

Rod Identity	Core II Average Kw/Ft	Core III Average Kw/Ft	Rod Average Burnup, MWD/MTM*	Location of Rod in Assembly
LZ	8.0	10.7	33,700	Center
BO	4.3	14.9	25,800	Peripheral
NI	5.0	11.2	27,000	Intermediate
RD	5.2	10.4	26,100	Intermediate
FS	5.3	9.6	25,500	Center
GL	6.0	8.8	26,500	Peripheral
MQ	8.0	6.1	28,800	Intermediate

* Estimated Peak-to-Average Burnup Ratios were 1.2 to 1.3, with expected peaks at 11 to 13 inches and 16 to 20 inches from the bottom of the rods.

Each of the seven rods as well as the assemblies from which they were removed were visually examined at the Saxton reactor site by underwater television to help assure that there were no gross anomalies. After arrival in the hot cell, each rod received the following inspections.

- a. Visual examination utilizing a stereo viewer with magnification range of 2X to 20X.
- b. Spiral profilometer scan and length measurement
- c. Single-channel gamma scan
- d. Fission gas sampling and analysis.

The rods were sectioned to provide metallographic, hydrogen analysis, and burnup samples from near the highest burnup positions on each rod. In addition, one metallographic section from the Core III peak power location of each rod was selected to determine microstructural changes where operating conditions were expected to be the most severe. Mechanical test samples (tensile and burst) were removed from six rods to determine the effects of fast fluence and/or axial location on strength and ductility. In conjunction with the mechanical tests, seven ring samples of cladding were analyzed for Mn-54 activity to determine fast fluence near the peak burnup location of each rod; two additional ring samples from intermediate power rod FS were analyzed for Mn-54 activity to estimate the axial distribution of fluence. A summary of the overall mid-life sampling plan is given in Table 3-5.

3-2.2 On-Site Examinations

Visual examination of the two loose lattice assemblies from which the MOL rods were removed confirmed that the design modifications made for Core III successfully eliminated the enclosure buckling of the type observed at end of Core II.^[1] The rods in the sampling plan were removed from their respective assemblies and examined visually with the aid of underwater television. This examination revealed no anomalies in the cladding or end plugs. It also showed significant crud deposits in the high heat flux areas and negligible crud in the grid contact areas and near the rod ends. This observation was consistent with the apparent crud distribution on rod RR, as described in Section 3-1.2.

TABLE 3-5

SAXTON PLUTONIUM PROGRAM CORE III MIDLIFE POST-IRRADIATION EXAMINATION SAMPLING PLAN

Rod I.D. #	Assembly Location	Rod Location	Estimated Rod Peak Burnup	Met.	Tensile	Burst	Mn-54	Clad H ₂	α Autoradiog.	β - γ Autoradiog.	Nd-148	HE ⁽²⁾
LZ	D-3	F-5	41,000	2	----	---	---	1	1	1	2	2
BC	D-2	J-1	34,000	2	2	1	1	1	1	1	1	1
NI	D-2	H-2	33,500	2	----	2	1	1	---	---	1	1
RD	D-2	G-3	32,000	2	2	1	1	1	---	---	1	1
FS	E-4	D-5	32,000	2	1	1	3	1	---	---	1	1
GL	D-2	D-8	33,000	2	1	2	1	1	---	---	1	1
MQ	E-4	G-2	36,000	2	2	1	1	1	1	1	2*	2*

NOTES: 1. All rods received: visual examination with photos as needed; profilometry and length measurements; fission gas sampling and analysis; single-channel gamma scan.

2. HE package includes U-234, -235, -236, and -238; Pu-239, -240, -241 and -242; and Pu-239/U-238.

*One of the burnup samples on rod MQ is a radial sample including 10 samples drilled from different radii with analyses for HE and Nd-148.

3-2.3 Non-Destructive Examinations in Hot Cell

All seven rods in the mid-life sampling plan were shipped from the Saxton reactor site to the hot cell facility of the Battelle Memorial Institute (BMI)* in Columbus, Ohio. All of the rods except for NI were transferred to the hot cells in special holders to minimize damage to crud deposits.

a. Visual Exams

Detailed visual examinations indicated that the rods were free of hydride blisters, swelling, collapsed areas, cracks or other defects. Crud thickness appeared to depend largely on rod power (heat flux), with the thickest deposits observed on rod BO and the thinnest deposits observed on rod MQ. Furthermore, the axial variation of crud also paralleled the power profile, i.e., the most extensive crud on a given rod was generally in or near the peak power positions (11 to 13" and 17 to 20"). Examples of these conditions are shown in Figures 3-11 and 3-12.

b. Length Measurements

Length measurement data obtained on the MOL rods are given in Table 3-6. They show that the additional length increases which occurred in Core III were small compared to those determined at end of Core II (~.03 to .05 percent vs .14 to .23 percent) and suggest that such increases are not linear with irradiation time or burnup. However, the data indicate a trend of increasing rod growth with higher fluence and greater incremental growth in Core III for the higher power rods (BO, NI and LZ). Both of these trends are consistent with the length changes observed for rods at end of Core II.[3]

c. Profilometry

The profilometry consisted of a continuous helical scan from a position about 1" above the bottom end of the fuel rods to the plenum region at the top, a distance of approximately 36 inches. Figures 3-13 through 3-19 summarize the reduced data for the seven rods profiled at mid-life; they show mean, minimum and maximum diameters at specific axial locations representative of the entire fuel rod. Note that selected areas of six rods were plated with nickel for edge preservation prior to profilometry. Thus, no data are available at these positions. A typical section of the trace from high power rod NI is shown in Figure 3-20.

*Hot cell operations for both mid-life and end-of-life rods were conducted by BMI under contract to the Westinghouse Nuclear Fuel Division.

Grid Scratch ↓

2608 30" from Bottom 4X
Typical of Moderate Crud Near Top

Grid Scratch ↓

2492 13" from Bottom 4X
Most Heavily Crudded Section of Rod

2495 7" from Bottom 4X
Beginning of Significant Crud Near
Bottom of Rod

2496 4-1/4" from Bottom 4X
Nearly Crud Free Surface in Grid
Contact Area (Light crud begins
above contact)

Figure 3-II Variation of Crud with Axial Location on Highest
Power Rod B0

2616 27" from Bottom 4X
Light Crud in Upper Section of Rod

2613 20" from Bottom 4X
Representative of Thickest Crud on Rod

2615 24.5" from Bottom 4X
Variable Crud in Grid Area

2609 3" from Bottom 4X
Crud Free Area on Bottom End

Figure 3-12 Variation of Crud with Axial Location on Low
Power Rod MQ

(Note: Circumferential Scribe Marks Intentional)

TABLE 3-6

SAXTON MIDLIFE LENGTH DATA

Rod Identity	Fabricated Length (inches)	Reconstitution Length (inches)	Core III MOL Length (inches)	Core III Incremental Length Increase ($\% \Delta L / L_o$)	Rod Average Fast Neutron Fluence at MOL ($10^{21} \text{ n/cm}^2 > 1 \text{ Mev}$)	Total Length Increase ($\% \Delta L / L_o$)
LZ	39.059	39.148	39.167	0.046	3.2	0.277
BO	30.064	39.119	39.140	0.054	2.0	0.195
NI	39.056	39.139	39.154	0.038	2.5	0.251
RD	39.082	39.129	39.139	0.026	2.0	0.146
FS	39.062	---	39.148	---	2.3	0.220
GL	39.057	---	39.138	---	2.1	0.207
MQ	39.060	39.146	39.159	0.033	2.9	0.253

Note: FS and GL were not measured at Reconstitution (Core III BOL)

Figure 3-13 Profilometer Data for Saxton Fuel Rod LZ

Figure 3-14 Profilometer Data for Saxton Fuel Rod BO

Figure 3-15 Profilometer Data for Saxton Fuel Rod NI

Figure 3-16 Profilometer Data for Saxton Fuel Rod RD

Figure 3-17 Profilometer Data for Saxton Fuel Rod FS

Figure 3-18 Profilometer Data for Saxton Fuel Rod GL

Figure 3-19 Profilometer Data for Saxton Fuel Rod MQ

3-33

Figure 3-20 Typical Section of Profilometry Trace, Fuel Rod NI, Near Peak Heat Flux Position

Comparison with profilometer data taken on two of these rods at end of Core II^[3] shows that the highest burnup rod, LZ, had negligible change in mean diameter as result of irradiation in Core III through mid-life. In contrast, rod B0, which operated at low power in Core II but at much higher power in Core III, exhibited diametral increases of up to 1.2 mils near the peak heat flux positions. None of the profilometer scans revealed any evidence of hydride blisters, bulges, significant ridging (in excess of ~0.5 mil), ovality greater than ~4 mils, fretting or other anomalies.

d. Gamma Scanning

All seven rods in the sampling plan were scanned with a sodium iodide detector measuring gross gamma activity with energies greater than 0.5 Mev. The data collected were full length scans using a constant traverse rate of 2 inches per minute, a detection slit width of 0.050 inch and a counting interval of 1 second. The system is capable of detecting gaps in the fuel column approximately 0.1 inch. The data reflect the relative axial distribution of power and burnup during Core III. Reduced scale traces of the seven MOL rods are shown in Figures 3-21 through 3-27. In general, the scans show two "peaks" in gamma activity--one at the Core II peak power location (between 16 and 20") and the other at ~11-12", which was the position of highest power during Core III. The scans also exhibit activity depressions at the grid locations, especially the second and third grids at 14-15" and 24-25", respectively. The only significant anomaly in the gamma scan data of the MOL rods was a sharp downward spike at the 21" location of rod NI (Figure 3-23), indicating a small gap of ~0.1" in the fuel column.

3-2.4. Destructive Examinations

a. Fission Gas Release

Each of the seven rods in the MOL sampling plan was punctured in a calibrated vacuum system in order to collect and sample the contained gases. Samples of the released gases were analyzed by mass spectrometry. The results, including those from rod RR, are summarized in Table 3-7. The krypton and xenon isotopic data, as given in Appendix A, were essentially the same as for rod RR and are considered typical of mixed $\text{PuO}_2\text{-UO}_2$ fuel. It should be noted that certain of the results in Table 3-7 are slightly different from those reported previously.^[5] The reasons for these differences are as follows:

1. Re-evaluation of all fission gas collection data has indicated that, except for rod B0, the total volume of gas released should be based on pressure change measurements at the hot cell immediately after rod puncturing. The two methods

Figure 3-21 Rod LZ Gamma Scan Data Plot

Figure 3-22 Rod BO Gamma Scan Data Plot

Figure 3-23 Rod NI Gamma Scan Data Plot

Figure 3-24 Rod RD Gamma Scan Data Plot

Figure 3-25 Rod GL Gamma Scan Data Plot

Figure 3-26 Rod FS Gamma Scan Data Plot

Figure 3-27 Rod MQ Gamma Scan Data Plot

TABLE 3-7

SAXTON CORE III MOL FISSION GAS RELEASE DATA

Rod Identity	Core III Rod Average Power, kw/ft	Rod Average Burnup (MWD/MTM) (1)	Total Vol. of Gas Released (cm ³) (S.T.P.) (4)	Gas Composition, Vol. %									Measured Fractional Release %
				He	N ₂	Ar	Kr	Xe	O ₂	CO ₂	H ₂ O	H ₂	
LZ	10.7	33,700	160.7	7.84	1.81	.18	5.24	84.4	.38	<.01	.07	.07	32.0
				7.98	1.87	.18	5.36	84.4	.28	<.01	.02	<.01	--
BO	14.9	25,800	146.0	6.80	7.52	.37	4.89	78.7	1.65	<.01	<.01	.08	37.0
				6.70	7.26	.36	4.85	78.9	1.89	<.01	.06	.06	--
NI	11.2	27,000	131.2	8.68	.03	.19	6.00	84.4	<.01	<.01	.04	.25	34.0
RD	10.4	26,100	121.4	8.66	.04	.31	5.32	85.5	<.01	---	.02	.17	33.0
FS	9.6	25,500	97.4	10.4	.20	.39	5.25	83.7	.03	<.01	<.01	.07	26.0
GL	8.8	26,500	107.6	10.6	1.38	.44	5.30	82.1	.04	---	.05	.10	27.0
MQ ⁽²⁾	7.0	28,000	91.7	2.84	79.80	.96	.63	15.3	.12	<.01	.2	.08	--
				2.52	79.05	.88	.40	17.0	.03	---	---	.10	--
RR ⁽³⁾	9.8	25,100	123.0	8.94	.78	.27	5.99	83.9	.01	---	---	.15	34.0

- (1) Rod average values normalized to measured Nd-148 burnup
- (2) Backup analysis performed at Waltz Mill
- (3) Data previously reported in Section 3.1.3 of this report.
- (4) Total volumes of gas collected are based on hot cell pressure drop measurements for all rods except BO.

used in this program to determine total volume of gas release and the anomalies associated with rod B0 are discussed in Appendix C.

2. The values of fractional fission gas release given in Reference 5 were computed on the basis of nominal fuel density and volume. However, recalculation of fractional releases utilizing measured as-fabricated fuel stack heights and weights along with corrected total volumes and measured burnups gives slightly higher values.

As expected, the results indicate a trend of increasing gas release with Core III power. For example, rods which operated at peak powers above ~ 16 kw/ft in Core III (B0, N1, LZ, RR and RD) all had fractional releases of 30 percent or higher. Intermediate power rods FS and GL showed somewhat lower releases. The analysis of gases from rod MQ implied a defected rod. Because of this, all non-destructive data were reviewed to clarify the condition of the rod when it was removed from the reactor and when it was first examined in the hot cell. However, no evidence of failure was noted. Subsequent metallographic examination of the cladding at the 18.75" plane revealed extensive hydriding over an arc of $\sim 45^\circ$. Therefore, on the basis of the fission gas data and metallography, MQ was identified as a suspected failed rod.

The results of the MOL fission gas release measurements also show higher total gas collected than for comparable power rods at end of Core II^[3], e.g., 161 cm³ from rod LZ vs 87 cm³ from two of the highest power pellet rods (TE and TP) at end of Core II. These differences, however, are consistent with the significantly higher rod average burnups of the rods removed at mid-life of Core III. On the other hand, the fractional releases of the highest power rods in each group were approximately the same. Comparison of fractional releases for the center 3 x 3 rods RR and LZ shows virtually no difference as a result of the somewhat higher burnup and larger number of load follow cycles experienced by rod LZ. The two rods had nearly identical power histories in Core II and Core III until the 1970 shutdown, when rod RR was removed. Rod LZ remained in the center 3 x 3 until the MOL shutdown and received an additional exposure of about 2000 EFPH, equivalent to 8,700 MWD/MTM, and 326 more load follow cycles. Despite these differences, the fractional releases for rods LZ and RR were 32 percent and 34 percent, respectively.

b. Metallographic Examination

Two metallographic sections from each rod were prepared by the methods described in Appendix B. Most of the sections had been nickel plated immediately after the initial visual examination for improved preservation of external surface features. The plating consisted of a silver strike by chemical reduction followed by electroplating in a nickel sulfamate bath. These samples were examined to determine clad oxidation and hydride

precipitation, fuel-clad bonding and general fuel microstructure. The principal features observed were as follows:

1. Cladding -- External corrosion film measurements are summarized in Table 3-8. The thickest film measured was 1.4 mils on one of the samples from center 3 x 3 rod LZ (Figure 3-28). Low power rod MQ was the only other rod which had an oxide film in excess of 1.0 mil. Since this rod had operated at high power in Core II, it is probable that most of the film buildup occurred during Core II. The maximum oxide thicknesses observed are consistent with the trend established by the lead Core II rods and by rod RR, which was removed from Core III in mid-1970. On the other hand, high power rods BO and NI exhibited thinner oxide films--typically 0.5 to 0.6 mil. Since these rods were deduced to have had very thin films (<0.3 mil) at end of Core II, their oxidation rate was apparently greater during Core III (3720 EFPD in Core III vs 9400 EFPD in Core II). On several metallographic sections there was evidence of intermittent thin deposits of adherent crud, typically 0.1 to 0.3 mil thick. An example of this crud is shown in Figure 3-28.

Hydride precipitation in the cladding of loose lattice rods was generally light to moderate. The orientation of hydrides was typically circumferential or random. Figures 3-29 and 3-30 illustrate the nature and extent of hydriding at the peak power positions of rods LZ and BO, respectively. As shown in Table 3-9, subsequent analyses of cladding ring samples by hot vacuum extraction techniques confirmed that hydrogen uptake during Core III operation was not appreciably higher than Core II; the hydrogen levels for the mid-life rods were from 66 to 111 ppm, as compared to 64 to 93 ppm for the pellet fuel rods analyzed at end of Core II.^[3]

The only anomalous hydride precipitation observed in rods removed at mid-life was in low power rod MQ at the 18.7" location, where extensive hydriding occurred near the outer surface over an arc of $\sim 45^\circ$. This condition is illustrated in Figure 3-31. In contrast, the 12" plane of the same rod was free of heavy hydriding and appeared to have a normal structure. This anomaly could have been related to the unusual hydriding which occurred in several M-series rods in Core II^[3,6], particularly since rod MQ contained fuel from the same pellet batch as these other rods.

2. Clad-Fuel Interface

As with rod RR, the higher power mid-life rods displayed more clad-to-fuel bonding than seen on any rods at end of Core II. An example of this bonding is shown in Figure 3-32. In addition, the residual volumes of the fuel-clad diametral gaps and radial cracks were generally less than

TABLE 3-8

SUMMARY OF MOL CORROSION MEASUREMENTS
AND INFERRED CORE III CORROSION

Rod No.	Sample Location In from Bottom	Range of Oxide Thickness (mils)	Estimated Max. Core II Oxide ⁽¹⁾ (mils)	Incremental Core III Oxide ⁽²⁾ (mils)
LZ	12.0	0.3 - 1.2	0.8	0.4
	20.8	1.1 - 1.4	0.8	0.6
BO	11.0	0.4 - 0.6	0.3	0.3
	18.0	0.5 - 0.6	0.3	0.3
NI	12.0	0.4 - 0.6	0.3	0.3
	18.0	0.3 - 0.5	0.3	0.2
RD	12.0	0.3 - 0.7	0.4	0.3
	18.0	0.4 - 0.6	0.4	0.2
FS	12.0	0.3 - 0.9	0.5	0.4
	18.0	0.3 - 0.8	0.5	0.3
GL	12.0	0.3 - 0.6	0.5	0.1
	18.8	0.4 - 0.6	0.5	0.1
MQ	12.0	0.4 - 1.1	0.8	0.4
	18.8	0.3 - 1.2	0.8	0.4

(1) Deduced from oxide thickness measurements made on comparable power sections at end of Core II^[3]

(2) Maximum EOL oxide less estimated maximum oxide at end of Core II

NOTE: THE OXIDE FILM HAS CRACKED PARALLEL TO THE CLAD. THE MAXIMUM THICKNESS (EXCLUDING THE CRACK) IS 1.40 MILS.

Figure 3-28 Maximum O. D. Oxide Film, Fuel Rod LZ, 20.75 Inches from Bottom

NOTE: THE O.D. OXIDE FILM IS PARTIALLY CRACKED ALONG THE CIRCUMFERENCE. PART OF THE LAYER OF NICKEL PLATING CAN BE SEEN ON TOP OF THE OXIDE IN THE RIGHT CENTER OF THE PICTURE

Figure 3-29 Clad Hydriding, Fuel Rod LZ, Peak Heat Flux Location, 12 Inches from Bottom

B0-11-11

100X

Figure 3-30 Typical Clad Hydride Precipitate Level, Rod B0,
11 Inches from Bottom

TABLE 3-9
CLAD HYDROGEN ANALYSIS

Rod ID	Sample Location, Inches from Bottom	Individual Values (ppm)	Hydrogen Concentration (1) (ppm) Average
LZ	20.75 - 21.0	102, 103	103
BO	18.75 - 19.0	79, 81	80
FS	18.75 - 19.0	68, 72	70
GL	18.75 - 19.0	76, 79	78
MQ ⁽²⁾	18.75 - 19.0	105, 116	111
NI	18.75 - 19.0	70, 72	71
RD	18.75 - 19.0	62, 70	66

(1) Average of two samples.

(2) Rod MQ ring sample was taken at 18.75 to 19.0 inches from the bottom of the rod. It was located immediately above the transverse met section which showed extensive hydriding.

MQ-18.75-30

100X

Figure 3-31 Heavy O.D. Hydride Precipitation, Rod MQ,
18.75 Inches from Bottom, 225°, Transverse Section

Neg. LZ-12-33

500X

Figure 3-32. Apparent Fuel-Clad Chemical Bonding in Rod LZ,
12 Inches from Bottom of Rod

those of Core II rods. Figure 3-29 clearly shows the proximity of the fuel to the clad in lead burnup rod LZ. These observations suggest progressive closure of the fuel-clad gap with increasing irradiation. None of the mid-life samples, however, exhibited the inner surface reaction zones of the type seen previously on rod RR.

3. Fuel Structure

All macrosections of mid-life fuel displayed the usual pattern of radial cracks, and the sections which operated at linear powers >13 kw/ft showed circumferential cracking as well. Large gas bubbles were visible in the periphery of the fuel outside the region of grain growth. Columnar grain growth was evident in the macrostructures from rods BO and NI. In addition, the two sections from the lead burnup rod LZ, contained a series of radially oriented pores in the central region which gave the appearance of columnar grains. Rods BO and NI also showed a well defined circular pattern of large fission product particles near the center of the macrosections. Several of these macrostructural features are illustrated in Figure 3-33.

In general, microstructures of MOL fuel were similar to those of Core II fuel and rod RR except where sections had operated at higher power levels in Core III, as for example the sections from rods BO and NI. Generally the microstructural examinations confirmed the presence of the features seen during macroexaminations (e.g., radial and circumferential cracks, columnar grain growth in rods BO and NI, large gas bubbles near the periphery of the fuel, etc.).

In the scanning of the fuel microstructures from the periphery to the center, the major features observed were as follows:

- a. Gas bubbles associated with PuO_2 particles
- b. A region of relatively low porosity
- c. Equiaxed grain growth
- d. Columnar grain growth in certain sections (rods BO and NI)
- e. Incipient central hole in one section from Rod BO
- f. Fission product precipitates in the regions of grain growth.

Several of these features are illustrated in Figures 3-34 through 3-37. The MOL fuel structures varied from one of obvious columnar grain growth and a central void in rod BO

Figure 3-33 . Photomicrograph of a Transverse Section of Fuel Rod BO,
17 Inches from Bottom

Neg LZ-20.75-32

X500

Figure 3-34 Gas Bubble Concentration in a PuO_2 Rich Area in Rod LZ, 20.75 Inches from Bottom

Neg LZ-16.75-29

X500

Figure 3-35 Large Gas Bubble and Fission Products in PuO_2
Rich Area of Rod LZ, 16.75 Inches from Bottom,
Near Edge of Equiaxed Grain Growth Region

Neg B0-17-20

150X

Figure 3-36 Region of Columnar Grain Growth in
Rod B0, 17 Inches from Bottom

Neg B0-17-8

150X

Figure 3-37 Central Region of Rod BO, 17 Inches from Bottom, Showing Large Precipitates, Equiaxed Grains, and Spheroidal Pores

(peak linear power >19 kw/ft) to one showing only limited equiaxed grain growth in rod MQ (~10 kw/ft). These variations are consistent with the structures expected, based on estimated peak powers of these rods.

As with fuel structures seen at end of Core II, there were aggregations of pores in the PuO_2 particles near the periphery of the fuel (Figure 3-34). The volume of these pores, however, appeared to have increased significantly as a result of Core III operation. Another feature of the porosity was the virtual absence of the fine as-fabricated pores in a narrow zone surrounding the grain growth region. In the region of grain growth, most of the porosity was observed on grain boundaries. Furthermore, no pores associated with the original PuO_2 particles were found in the grain growth area, presumably due to homogenization of PuO_2 and UO_2 in the higher temperature region of the fuel.

4. Autoradiography

Alpha and beta-gamma autoradiographs of the peak power sections from rods MQ, LZ, and BO were prepared. The autoradiographs indicate the degree of homogenization of PuO_2 particles, the extent of local plutonium generation, and the presence of any significant segregation of fission products. The specific rods were selected because MQ represented a high burnup at relatively constant power of ~10 kw/ft, LZ was the highest burnup rod removed from Core III at mid-life, and BO experienced the highest power of any rod removed.

Alpha radiographs from all three rods showed evidence of discrete PuO_2 particles in the periphery of the sections and homogenization toward the center. These observations are consistent with results at end of Core II and for rod RR, where homogenization also occurred at temperatures sufficiently high to produce equiaxed grain growth. In rod MQ very little homogenization occurred, while in rod BO homogenization was observed out to about two thirds of the section radius. The alpha radiographs also showed higher alpha activity near the periphery of all sections of the fuel, due to the greater production of plutonium isotopes in this higher burnup region. These conditions are illustrated in Figure 3-38.

The β - γ autoradiograph of rod BO (Figure 3-39) exhibits typical features for fuel which has experienced columnar grain growth. The central region contains a zone of high fission product activity surrounded by a zone of low activity. The pattern of behavior observed in the autoradiographs of the sections from rods MQ and LZ is consistent with those previously reported for sections of similar power histories (See Section 3-1.4 and Reference 3).

Figure 3-38 Alpha Radiograph of Rod BO.
(White Areas Represent High Alpha Activity)

ZERO DEGREE

Figure 3-39 β - γ Autoradiograph of Rod BO,
(Dark Spots Represent High β - γ Activity)

c. Fluence Measurements

Fast neutron fluence measurements were made on selected cladding samples to provide an improved basis for interpreting mechanical test data. Nine samples from seven MOL rods were analyzed for manganese-54 activity and iron content. The results were used to infer the fast neutron fluence ($E > 1$ Mev). The measured Mn-54 activity and the resulting fluence are shown in Table 3-10. As expected, the highest fluence sample was from the lead burnup rod, LZ. However, high power rods BO, NI and RD showed moderately high fluences at their 19-20" locations. The results also indicate that the rods which operated at low or intermediate power in Core III had significantly lower cumulative fluences. In addition, measurements made on three samples from rod FS indicated essentially equal fluences at the 11.4 and 19.4 inch locations but lower fluence toward the top end of the rod, as expected. These axial variations in fluence are similar to those observed in several rods at end of Core II.^[3] Another feature of these data is that the cumulative fluences at Core III mid-life are only slightly higher than those for the peak burnup rods analyzed at end-of-Core II.

d. Burnup Measurements

One sample taken at or near the highest burnup position of each of the seven MOL rods was analyzed by mass spectrometric techniques to determine burnup and uranium and plutonium isotopic compositions. The results are summarized in Table 3-11 and indicate that the highest burnup was about 42,000 MWD/MTM in center 3 x 3 rod LZ. The rods which operated at low power in Core II but at high power in Core III, e.g., BO and NI, showed significantly lower peak burnups, as expected. Samples from rods with other power histories had intermediate burnups.

In addition, ten radial drill samples from near the peak burnup position of rod MQ were also analyzed for burnup and isotopic composition.

A detailed reduction of the burnup data and comparison of measurements with predictions are given in References 4 and 5.

e. Tensile Testing

Tensile testing of cladding sections was performed with a screw-driven 20,000 lb. capacity, Model TTD Instron machine, modified for hot cell use. Heating of the 6 in. long, full tube section samples was accomplished with a Marshall three-zone resistance furnace. Temperature controls provided an axial profile within $\pm 5^\circ\text{F}$ of the specified temperature (either 650 or 675°F).

Results of tensile tests performed on the samples from the MOL rods are shown in Table 3-12. Values of elongation in this

TABLE 3-10
FLUENCE RESULTS⁽¹⁾

Rod Identity	Sample Midpoint Location, Inches From Bottom of Fuel Stack	Measured Mn-54 ⁽²⁾ Activity, dpm/mg Fe x 10 ⁷	Fast Neutron Fluence, >1 Mev n/cm ² x 10 ²¹
LZ	20.38	5.26	3.9
NI	19.38	4.48	3.3
RD	19.38	4.25	3.2
GL	19.38	3.66	2.7
FS	11.38	3.78	2.8
FS	19.38	3.73	2.8
FS	27.38	3.03	2.3
MQ	27.13	2.81	2.1
BO	19.38	4.85	3.6

(1) End of irradiation for these rods was March 12, 1971.

(2) Mn-54 activities corrected to December 1, 1971.

TABLE 3-11
BURNUP RESULTS AND ISOTOPIC COMPOSITIONS (1)

Fuel Rods From Which Burnup Samples Were Taken	Sample Midpoint Location, Inches From Bottom of Fuel Stack (2)	Measured Burnup, MWD/MTM			Isotopic Compositions ⁽³⁾ , a/o								
		Heavy Element	Nd-148	$\frac{\text{HE-Nd}}{\text{Nd}} \times 100$	U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
FS	18.5	31700	32500	-2.5	.005	.488	.050	99.458	.367	60.842	29.342	7.930	1.519
NI	18.5	32400	33500	-3.2	.004	.477	.051	99.468	.388	60.337	29.580	8.073	1.620
RD	18.5	30900	31800	-2.8	.005	.487	.048	99.461	.331	60.553	29.987	7.689	1.441
BO	18.5	31900	32900	-2.9	.005	.483	.050	99.463	.365	59.753	30.408	7.897	1.576
LZ	18.75	40200	41800	-3.7	.004	.414	.061	99.520	.585	52.343	33.762	10.579	2.730
GL	18.5	30200	31500	-4.2	.005	.523	.050	99.422	.361	62.731	27.824	7.661	1.422
MQ	20.5	34800	35700	-2.5	.004	.463	.055	99.478	.445	58.571	30.234	8.842	1.908

- (1) End of irradiation for these rods was March 12, 1971.
- (2) Burnup samples had nominal lengths of 0.5 to 1.0 inch and were taken at or near the expected peak burnup location on each rod.
- (3) Analyses were performed between 11/11/71 and 12/15/71.

TABLE 3-12

TENSILE TEST DATA - MID-LIFE SAMPLES

Rod Identity	Axial Location (In. from Bottom)	Est. Fluence, (10^{21} n/cm ²)	Pre-MOL Kw/ft ⁽¹⁾	Test Temp (°F)	0.2% Yield Strength (10^3 psi)	Ultimate Strength (10^3 psi)	Uniform Elong. (%)	Total Elong. (%)
BO	11-17	3.8	17.0	650	61.4	65.6	2.4	7.9
BO	25-32	2.7	12.8	650	58.1	68.9	2.6	10.0
RD	3-9	2.9	12.8	650	62.2	70.0	2.1	3.5
RD	12-18	3.4	15.7	650	60.5	65.4	1.9	5.2
FS	23-34	1.9	10.2	675	57.2	71.4	4.3	22.3
GL	12-18	2.8	13.8	675	60.5	71.5	2.7	8.2
HQ	12-18	2.8	7.9	675	70.4	77.4	2.0	5.3
HQ	23-34	1.8	5.5	675	66.0	75.1	1.4	4.7

(1) Average linear heat rating along specimen prior to MOL shutdown.

table are different from those reported previously^[5] as a result of reanalyzing the stress-strain curves and calculating the elongation on a basis consistent with ASTM recommendations.

As indicated in Table 3-12, the variation in tensile properties within the MOL data do not appear to be clearly related to differences in fluence or linear power (clad irradiation temperature). On the other hand, the two samples from the lowest power rod (MQ) exhibited the highest strengths, which is consistent with expectations. Since MQ was judged as a suspected failed rod, the properties of these samples may also have been influenced by abnormal hydriding of the clad.

In comparison with end of Core II results^[3], the MOL samples had significantly higher yield and tensile strengths and lower ductility. The differences were especially prominent in yield strength, where MOL values at 675°F were from 57,000 to 70,000 psi as compared with 42,000 to 57,000 psi for Core II material of similar power history. Large differences were also noted in uniform elongation, with a range of 1.6 to 3.9 percent for MOL samples vs 2.5 to 7.3 percent for EOC II. The reasons for these differences are not obvious but could be related to the reduced reactor power (19 MWt) over 12 of the last 16 days of operation prior to the MOL shutdown. The small differences in fluence between end of Core II and MOL of Core III (range of 1.5 to 3.3×10^{21} vs 1.9 to 3.8×10^{21}) are not believed to be sufficient to account for the above differences in tensile properties. Despite the lower elongations, the fracture areas of all samples displayed generally ductile behavior.

f. Burst Testing

The burst tests were conducted with fuel still in the cladding in a unit which utilized a hydraulic pump to pressurize the specimens and an in-line strain-gage transducer to measure the system pressure. Volume expansion during the test was monitored by a linear variable differential transformer (LVDT), which measured the displacement of the pump piston. A pressure-volume curve was generated by recording the outputs of the strain gage and LVDT. These in turn were converted to a plot of pressure vs. volume change (Figure 3-40), from which the 0.2 percent yield stress could be determined. Specimen heating to 675°F was accomplished with a quartz lamp furnace. The temperature of the center 3-inch section was controlled to $\pm 5^\circ\text{F}$. One end of each specimen was connected to the pressurization system; the other end was closed off with a blind high pressure fitting. This "closed end" arrangement provided a hoop-to-axial stress ratio of 2/1. The nominal rate of pressurization was 2000 psi per minute. Failure strains were measured from transverse metallographic sections taken at the plane of maximum deformation. Such a section is shown in Figure 3-41.

Figure 3-40 Pressure versus Specimen Volume Change,
Rod GL at 675°F

Figure 3-41 Burst Test Specimen, Transverse Metallographic Section of Burst Test Specimen from Rod NI, Used for Determining Failure Strains

The results of the burst tests performed on the MOL samples are given in Table 3-13. Unlike the tensile data, the yield and failure stresses of MOL specimens were in the same range as those of the higher strength Core II burst samples. A comparison of failure strains was not possible because of the large uncertainties and scarcity of Core II strain data. Generally, the MOL burst strains indicated moderately high ductility. (Except for one sample, all burst strains were greater than 4 percent). The four samples taken from the 3-11 inch location of high and intermediate power rods show excellent ductility (failure strains of 16 to 19 percent).

These results suggest a possible correlation of burst strains with Core III linear power prior to MOL (clad irradiation temperature), i.e., higher ductility with increased clad temperatures. A comparison of MOL burst strengths with uniaxial tensile strengths shows that they are generally comparable, e.g., all burst strengths were between 68,000 and 77,000 psi vs 65,000 to 77,000 psi for ultimate tensile strengths. As with the tensile results, there was no apparent correlation of burst strengths or ductility with fluence.

3-2.5. Summary of Performance of Mixed Oxide Fuel Through Core III Mid-Life

Hot cell examinations of selected rods removed at mid-life indicated good performance at peak burnups in the range of ~32,000 to 42,000 MWD/MTM. Visually, the external surfaces were free of blisters, bulges, cracks, white corrosion products and other defects. Like rod RR, all seven MOL rods displayed good dimensional stability. Fractional fission gas releases of the highest power rods were 34 to 37 percent, which were only slightly higher than those of lead rods at end of Core II. Although significant quantities of loosely adherent crud deposits were observed in many areas of the MOL rods, the corrosion of the cladding showed no anomalies, with a maximum of 1.4 mils of external oxide on lead burnup rod LZ and ~0.6 mil of external oxide on the peak power rods. In addition, there was only a small increase (maximum of ~20 percent) in hydrogen level as compared with end-of-Core II samples. The microstructures of the highest power fuel showed several features, e.g., columnar grain growth and extensive fuel-clad bonding, not seen previously. However, there was no evidence that any of these changes would limit the performance of the fuel. Tensile and burst testing of MOL cladding samples revealed that the cladding had retained significant ductility.

TABLE 3-13

BURST TEST DATA AT 675°F - MOL SAMPLES

Rod Identity	Axial Location (In. from Bottom)	Est. Fluence (10^{21} n/cm ²)	Pre-MOL Power, ⁽¹⁾ (Kw/ft)	0.2% Yield Stress, ⁽²⁾ (10^3 psi)	Failure Stress, ⁽²⁾ (10^3 psi)	Failure Strain, (%)	Wall Thickness Reduction, (%)
BO	3-11	3.4	15.0	67.1	70.4	19.0	24
NI	3-11	3.1	14.5	67.7	71.7	16.1	24
NI	26-34	2.3	10.7	64.5	69.7	6.3	36
RD	26-34	2.2	9.6	63.2	71.1	4.6 ⁽³⁾	4 ⁽³⁾
FS	3-11	2.5	12.3	63.8	69.7	18.3	23
GL	3-11	2.6	13.4	65.1	68.4	18.3	33
GL	28-36	1.6	6.1	73.0	76.3	2.6	25
MQ	3-11	2.5	7.7	70.4	72.4	4.8	28

(1) Average linear heat rating along specimen just prior to MOL

(2) Based on thick wall formula for generalized stress.

(3) Pinhole failure.

3-3. RODS REMOVED AT END OF LIFE

3-3.1. Sampling Plan

The end of life (EOL) sampling plan is given in Table 3-14. The rods originally selected for examination at the end of Core III included a pair from each of four different Core III power groups. The distribution of the rods within the various power groups was similar to the MOL sampling plan and thus permitted a comparison of fuel performance at varying Core III burnup levels. Note that the two rods which achieved the highest burnup (rods IM and PF, both from the center 3 x 3 assembly) were included in the program. In addition, all rods in the plan had been previously scanned with a profilometer during reconstitution of Core III.

As noted previously in Section 2, abnormally high coolant activity was observed on several occasions between the mid-life start-up and end-of-life. The level of activity indicated the presence of a significant number of defected rods. Subsequent leak testing and other non-destructive examinations, performed as part of a Westinghouse funded program, identified 37 defected loose lattice rods, all from locations which experienced relatively high power between MOL and end of life. Of these, 33 rods had operated at a continued high power level throughout Core III; the other four rods had been inserted into the loose lattice at MOL⁽⁷⁾ and had experienced linear power increases in excess of 10 kw/ft over their end-of-Core II power levels. However, none of the rods in the original EOL sampling plan, including the two highest power rods, happened to be failed. Because of these observations, the end-of-life sampling plan was revised to include the examination of one failed rod (JX) from the group of 33 in place of one of the non-failed rods. Rod JX was typical of the failed rods with respect to power history, location in the core, and preliminary visual appearance. The primary objective of examining rod JX was to characterize the failure.

The scope of examinations for each rod in the end-of-life plan was similar to that at mid-life, e.g., all rods received visual exams, diameter profile scans, length measurement and gamma scans. Furthermore, the rods were sectioned to provide microstructural, hydrogen, burnup and mechanical test samples from locations representative of high power, burnup or fluence. Additional metallographic samples from failed rod JX were examined in lieu of fission gas sampling and analysis.

TABLE 3-14

SAXTON PLUTONIUM PROGRAM CORE III END-OF-LIFE POST-IRRADIATION SAMPLING PLAN

Rod ID	Assembly Location	Rod Location	Estimated Rod Peak Burnup (MWD/MTM)	Met.	Tensile	Burst	Mn-54	Clad H ₂	α Autoradiog.	β - γ Autoradiog.	Nd-148 Burnup	H.E. (2) Burnup	Special (3) Isotopes
IM	D3	D5	50500	2	1	1	1	1	1	1	2 ⁽⁴⁾	2 ⁽⁴⁾	1
PF	D3	E6	51000	2	1	1	1	1	1	1	1	1	1
BE	D3	F1	43000	2	1	1	1	1	-	-	1	1	-
BK	E4	A8	44900	2	1	1	1	1	1	1	1	1	1
GM	E4	A2	41500	2	1	2	1	1	-	-	1	1	-
JK ⁽⁵⁾	D3	D7	44000	3	-	-	1	1	-	-	1	1	-
LS	E4	H3	42000	2	1	1	1	1	-	-	1	1	1
FI	E4	F1	40900	2	2	1	1	1	1	1	1	1	-

- NOTES: (1) All rods receive: visual examination with photos as needed; profilometry and length measurements; fission gas sampling and analysis; single-channel gamma scan.
- (2) HE package includes L-234, -235, -236 and -238; Pu-239, -240, -241 and -242; and Pu-239/U-238.
- (3) Special isotopes package includes Pu-236 and -238; Np-237; Am-241 and -243; and Cm-242 and -244.
- (4) One of the burnup samples on rod IM is a radial sample including 10 samples drilled from different radii with analyses for HE and ND-148. In addition α and β - γ autoradiographs and a metallurgical mount will be prepared before drilling.
- (5) Additional metallography will be performed in lieu of fission gas sampling and analysis.

3-3.2. On-Site Examinations

At the Saxton site, each of the seven loose lattice assemblies was leak tested in the pool to determine its acceptability for shipment in conventional containers. These tests showed three assemblies (from core locations D2, D3 and D4) with strong leak indications and one assembly (from core location C2) with suspect indications. Subsequently, five loose lattice assemblies, including the above mentioned four, were shipped to the Battelle Memorial Institute hot cells for removal and examination of selected rods. The identifications and core locations of these five assemblies are indicated in Appendix B.

The other two loose lattice assemblies (from core locations E2 and C4) were judged to be non-leakers, and since they did not contain any fuel rods scheduled for post-irradiation examination they were shipped directly from the site to the reprocessing plant at Savannah River.

3-3.3. Non-Destructive Examinations in Hot Cell

a. Visual Examinations

Each of the rods in the sampling plan was visually examined over its entire length to determine clad surface conditions and the extent and distribution of crud and corrosion products. With the exception of failed rod JX, the rods showed no evidence of cracks, blisters, bulges, or other significant defects.

Of the seven non-failed rods examined, only high power rod BE showed any surface anomalies. Numerous non-lustrous white patches were observed, even after nylon brush cleaning, at several axial locations between 8 and 14 inches* and to a lesser extent between 17 and 20 inches.

These patches appeared as depressions of several mils depth and were usually observed in areas where the adjacent clad surface was rough. A typical patch is illustrated in Figure 3-42. Subsequent recovery of normal fission gas from the rod indicated that none of these patchy areas had penetrated through the clad and that the rod was not defected. Rod BE also exhibited hard, adherent crud deposits (a few mils thick from visual estimates) in the high power positions between grids. In contrast, the lower and upper 6 inches of the rod and areas enclosed by the assembly grids were free of white patches and adherent crud.

*Axial locations are expressed as distance from the bottom end of the rod.

P3377 ROD BE at $11\frac{1}{2}''$ (225°)

10X

Figure 3-42 Typical White Patchy Area Adjacent to Heavy Crud (Dark) at Peak Power Location of Rod BE
(Note reference circumferential scribe marks to help estimate crud thickness)

Rod BK also had significant crud deposits in the high power positions between grids but did not show any of the white depressions seen on rod BE. Figure 3-43 shows the typical surface condition at the peak power location (~12"). No visual evidence of cracks, blisters, ridges or other anomalies was observed on this rod.

The remaining non-failed rods (FI, LS, GM, IM and PF) were also free of surface anomalies. Gray to white corrosion films were observed on these rods to varying degrees at locations between 6 inches and 34 inches. There was no discernible thickness to the films when examined on the stereoviewer at magnifications up to 30X. These thin gray and white films are illustrated in Figure 3-44. Although a few small areas of dark, non-lustrous deposits were observed, these five rods were essentially free of adherent crud.

Failed rod JX was similar in surface appearance to rod BE, but had more evidence of clad degradation in the high power positions. Much of the area between 8 and 14 inches and between 17 and 22 inches exhibited a rough surface with extensive white patchy appearance. An apparent defect in the rod is visible at an axial position of about 13" from the bottom (Figure 3-45).

Visual examination of rod PG, one of the four previously irradiated loose lattice rods inserted into assembly 17-2 (core location D2) at the mid-life shutdown, showed several surface conditions similar to those seen on rod JX. For example, much of the high power region was covered with hard adherent crud. In addition, there were numerous rough areas with white patchy depressions similar to the type observed on the non-failed rod BE and the failed rod JX. However, there was no obvious defect or evidence that the cladding had been breached.

Length Measurements

Length measurement data obtained on rods in the EOL sampling plan with their corresponding estimated fast neutron fluences are summarized in Table 3-15. They include measurements made during fabrication and at end of Core II (prior to reconstitution of Core III assemblies), as well as at end of life. As expected, the length increases in these rods were generally greater than those observed on MOL rods of similar power history. For example, the total length increases of the highest burnup rods (IM and PF) at EOL were .29 percent and .32 percent respectively, compared with .28 percent for rod LZ at MOL. Similarly, peak power rods BE and BK showed length increases of 0.23 percent, while the growth of MOL rod BO was 0.20 percent. The results also reveal a trend of greater length increases with higher rod average fluences, similar to that for the MOL results discussed in

P3800

12" - 315°

4X

Figure 3-43 Typical Surface Condition of Peak Power Section
of Rod BK Prior to Brush Cleaning

P 3279

GX

Figure 3-44 Appearance of Oxide Film on Rod FI, 18 Inches from the Bottom

NEG. 4043

4X

Figure 3-45 Surface Appearance of Rod JX in Defected Area (13.0 to 13.5 Inches from Bottom) Prior to Sectioning

TABLE 3-15
SAXTON END-OF-LIFE LENGTH DATA

Rod Identity	Fabricated Length (inches)	Core III BOL Length (inches)	Core III EOL Length (inches)	Core III Incremental Length Increase ($\% \Delta L/L_0$)	Rod Average Fluence at EOL ($10^{21} \text{ n/cm}^2, >1 \text{ Mev}$)	Total Length Increase ($\% \Delta L/L_0$)
IM	39.060	39.141	39.185	0.11	3.6	0.32
PF	39.067	39.143	39.180	0.09	3.5	0.29
BE	39.063	(1)	39.151	----	2.6	0.23
BK	39.067	39.132	39.156	0.06	2.9	0.23
GM	39.056	(1)	39.159	----	3.1	0.26
JX	39.065	39.116	39.169	0.14	2.8	0.27
LS	39.061	39.144	39.184	0.10	3.2	0.32
FI	39.060	39.144	39.177	0.08	3.1	0.30

(1) BE and GM were not measured at Core III BOL.

(2) Rod Average

Section 3-2.3. Except for failed rod JX, the data indicate that about 25 to 35 percent of the total rod growth occurred during Core III. These values are somewhat less than the Core III fraction of time at full power (6000 EFPH of a total of 15,300 EFPH). This observation suggests that rod growth was not linear with irradiation time. The overall results of rod growth at MOL and EOL are consistent with values obtained on Zircaloy cladding at two other laboratories.[8,9]

c. Profilometry

All eight rods were scanned with a profilometer after brush cleaning. The same equipment was used as for the mid-life rods to provide a continuous helical scan with 1/8" pitch along 36 inches of the rod. The data from each profilometer trace was reduced to provide maximum, minimum and mean diameters at ten pre-selected non-grid locations; these are summarized in Figures 3-46 through 3-53. Data could not be obtained in certain areas of rods BE and LS because these areas had been previously coated with epoxy for preserving the crud and oxide film.

As noted during visual examination, a significant portion of the surfaces of rods BE, BK and JX was covered with adherent crud which was not removed during brush cleaning. These deposits made analysis of the profiles of such rods difficult, as is evident from Figures 3-48, 3-49 and 3-50. However, subsequent examination of representative metallographic sections having adherent crud, e.g., on rods BE and BK, showed that the typical crud contribution was between 1.0 and 1.5 mils on the diameter. This difference appears to be consistent with estimates of the "crud effect" obtained by comparing mean diameters at nearby non-cruded areas with those of the axial locations in question.

Generally, all non-failed rods showed reduced diameters ("creepdown") in the intermediate and high power areas when compared to the low power extremities. Even the highest power rods, BE and BK, exhibited about one mil creepdown on this basis. The rods which operated at relatively low power in Core III (FI, GM and LS) showed somewhat more creepdown, up to about 1.8 mils. Comparison of EOL and reconstitution diameters showed that most of the rods experienced some further creepdown in Core III. This incremental creepdown ranged from zero in rods BE and PF to between 1.0 and 1.3 mils in rods IM, FI and LS. These trends are consistent with the diametral changes observed on rods from Core II[1,3] and those removed at Core III mid-life (See Section 3-2.3), i.e., there was more diameter reduction in the lower power rods. It is concluded, therefore; that increasing burnup up to 51,000 MWD/MTM had little effect on the diametral changes of the Saxton mixed oxide fuel rods.

Figure 3-46 Profilometer Data for Saxton Fuel Rod 1M

3-81

Figure 3-47 Profilometer Data for Saxton Fuel Rod PF

7419-47

Figure 3-48 Profilometer Data for Saxton Fuel Rod BE

Figure 3-49 Profilometer Data for Saxton Fuel Rod BK

Figure 3-50 Profilometer Data for Saxton Fuel Rod JX

3-85

Figure 3-51 Profilometer Data for Saxton Fuel Rod GM

Figure 3-52 Profilometer Data for Saxton Fuel Rod LS

Figure 3-53 Profilometer Data for Saxton Fuel Rod FI

The typical ovality indicated by the profilometer scans was one to two mils, although on several rods (e.g., BK) it was locally as high as ~4 mils. This range of ovality was essentially the same as for all rods profiled during reconstitution.^[3]

With the exception of the deteriorated areas on failed rod JX and the heavily crudded areas of rods BE and BK, the profilometry traces revealed no anomalous conditions, i.e., there was no evidence of hydride blisters, bulges, cavities or similar conditions. Moderate clad ridging was observed in several locations, but generally the diametral ridge heights were less than 0.5 mil. In no case did they exceed ~1.5 mil.

d. Gamma Scanning

The eight rods in the EOL sampling plan were gamma scanned in the same manner as the mid-life rods (See Section 3-2.3). As shown in Figures 3-54 through 3-61, the resulting traces show the same trends as those seen previously, e.g., two activity peaks corresponding to the highest burnup locations and slight depressions in activity at grid positions. The traces indicate that there were no gaps in the pellet columns greater than ~100 mils. There was evidence of minor pellet fragmentation near the top of the fuel column in rods GM and LS.

3-3.4. Destructive Examinations

a. Fission Gas Release

Puncturing of the seven non-failed EOL rods and collection of their fission gas were accomplished in the same manner as for the MOL rods. The results of the analyses are given in Tables 3-16 and Appendix A. The fractional release values shown are slightly different from those presented earlier^[10] because, 1) they were re-calculated on the basis of measured rod average burnups and, 2) they were corrected for actual fuel density and volume in the same manner as the MOL rods (See Section 3-2.4).

A comparison of Tables 3-7 and 3-16 shows that, as expected, the total gas volumes collected from the lead power and highest burnup rods were slightly higher than from comparable rods (LZ, B0 and NI) at mid-life. However the fractional releases of the highest power rods (BE and BK) were approximately the same as those of the highest power rods removed at mid-life (B0 and NI) -- in the range of 34 to 37 percent. Similarly, the releases from the two center 3 x 3 rods (IM and PF) were 28 and 32 percent, respectively, as compared with 32 percent observed for rod LZ at mid-life. These results indicate little

Figure 3-54 Rod IM Gamma Scan Data Plot

Figure 3-55 Rod PF Gamma Scan Data Plot

Figure 3-56 Rod BE Gamma Scan Data Plot

Figure 3-57 Rod 3K Gamma Scan Data Plot

Figure 3-58 Rod JX Gamma Scan Data Plot

Figure 3-59 Rod GM Gamma Scan Data Plot

Figure 3-60 Rod LS Gamma Scan Data Plot

Figure 3-61 Rod FI Gamma Scan Data Plot

TABLE 3-16.

SAXTON CORE III END-OF-LIFE FISSION GAS RELEASE DATA

Rod I.D. Number	Rod Average Burnup (MWD/MTM)	Total Volume of Gas Released (2) (cm ³ -STP)	Gas Composition, Vol. %										Measured Fractional Release (%)
			He	N ₂	Ar	Kr	Xe	O ₂	CO ₂	H ₂ O	H ₂	CH ₄	
IM	39,000	165.8	9.9	<.01	.26	6.28	83.5	<.01	<.01	<.1	.02	<.01	28
PF	37,500	173.6	9.5	.06	.17	6.25	84.0	<.01	<.01	<.1	.05	<.01	32
BE	30,200	148.2	9.1	<.01	.31	6.42	84.1	<.01	<.01	<.1	.03	<.01	34
BK	33,400	170.6	9.1	<.01	.29	6.31	84.2	<.01	<.01	<.1	.05	<.01	36
GM	31,900	73.3	11.7	.08	.47	5.83	81.8	<.01	<.01	.1	.03	<.01	15
LS	33,700	91.2	11.4	<.01	.22	5.96	82.4	<.01	<.01	<.1	.01	<.01	18
FI	31,000	88.8	13.3	.04	.55	5.78	80.3	<.01	<.01	<.1	.03	<.01	19

(1) Normalized to measured Nd-148 burnup.

(2) Based on hot cell pressure change measurements for all rods except GM.

change in fractional gas release as a result of the incremental burnup (5000 to 7000 MWD/MTM) and an additional 167 load follow cycles between mid-life and end of life.

As expected, the low power rods (FI and LS) showed lower fractional releases. These results cannot be compared directly with those at mid-life because the sister MOL rod, MQ, was identified as a suspect failed rod.[5] However, the fractional releases of 18-19 percent are consistent with expectations for rods which operated at relatively high power in Core II (peak of 11 to 13 kw/ft) and somewhat lower power throughout Core III. Note that their releases are also less than the 25 to 32 percent observed for rods CH, TE, TI, TP and TT at end of Core II.[3] Rods FI and LS had comparable power histories to these five rods in Core II. This difference reflects the lower release rate while operating at lower rod average powers during Core III.

The total volume of gas collected from intermediate power rod GM was significantly lower than that collected from other EOL rods, even the two low power rods. Its fractional release of ~15 percent was also low in comparison with the ~25 percent releases of MOL intermediate power rods FS and GL (See Table 3-7). The reason for this anomalously low release is not clear but could be the result of incomplete collection of gas from the rod, as suggested by the discussion in Appendix C.

b. Metallographic Examination

From each non-failed rod, two metallographic sections were prepared to determine significant microstructural features of the cladding and fuel, particularly as they relate to performance of the rods at high burnups. Failed rod JX was examined metallographically in several planes to characterize the failed region(s) as well as to examine fuel and clad structures in a non-defected area of the rod. The procedures for mounting and preparing these metallographic samples were essentially the same as used for the mid-life samples and are given in Appendix B.

1. Microstructure of Cladding

The samples from the two highest burnup rods, IM and PF, showed little or no further increase in external oxide thickness over the maximum observed in rod LZ, the highest exposure rod removed at mid-life (See Table 3-8).

Maximum film thicknesses in rods IM and PF were 1.5 and 1.2 mils, respectively, as compared with 1.4 mils for rod LZ. On the other hand, the typical oxide films of rods IM and PF were significantly thinner than the maximum thickness on the same rods, varying between ~0.5 mil to 1.0 mil around the periphery of the sections.

Rods BE and BK, which experienced very high power at the beginning of Core III, showed significantly different corrosion behavior than their sister rods (BO and NI) removed at mid-life. For example, rod BE had oxide thicknesses which varied from 0.7 mil to approximately 4 mils in the 12 inch plane, where an apparent white corrosion product was seen during visual examination. One such area is shown in Figure 3-62. At several circumferential positions there was evidence that the oxide had partially spalled, accounting for the rough surface appearance discussed previously for rod BE. The two sections from rod BK also showed more extensive oxidation than the comparable MOL samples. Typical oxide films were 0.7-0.8 mil, with a maximum of 1.0 mil, as compared to typical thicknesses of 0.4-0.5 mil and a maximum of 0.6 mil on rods BO and NI at mid-life. It should be noted, however, that rod BK did not exhibit any of the anomalously thick or spalling oxide of the type seen on rod BE (See Section 3-3.3).

Another unusual feature of the external surfaces of rods BE and BK was the presence of relatively hard, adherent crud with a thickness of 0.2 to ~1.0 mil. An example of this crud is shown in Figure 3-63. In addition, a soft porous crud up to about 3 mils thick was observed on the two samples from rod BE (Figure 3-64), where the rod surfaces had been preserved with a silica-filled epoxy coating.

The disproportionately thicker oxide on the high power rods at end-of-life indicates a higher corrosion rate during the 2200 EFPH's after mid-life than during the first 3700 EFPH of Core III operation. Further, the presence of significant quantities of adherent crud on the EOL rods, in contrast to little or no crud at MOL, suggests a change in the core environment, such as water chemistry, after mid-life with a resulting effect on crud deposition.

The first section of failed rod JX, at ~13 inches, showed surface features similar to those of rod BE at the 12 inch plane, including heavy oxidation of the outer clad surface. At one position the oxide had penetrated about 8 mils into the Zircaloy (See Figure 3-65). There was also clear evidence that some of the thick oxide had spalled, which accounts for the rough surface noted during visual examination and profilometry.

The 18 inch plane of rod JX also exhibited thick oxide on the outer surface but not to the same extent as at 13 inches. There was evidence of irregular reductions in clad wall thickness as a result of locally spalled oxide. The main feature of the microstructure in this plane was the extensive hydriding around most of the periphery, as indicated by numerous hydride precipitates and several areas of solid zirconium hydride. One of these solid hydride areas contained two small cracks, which originated at the external surface.

Figure 3-62 Abnormally Thick Oxide on Outer Surface of Rod BE, 12 Inches from the Bottom

Rods BE and BK, which experienced very high power at the beginning of Core III, showed significantly different corrosion behavior than their sister rods (BO and NI) removed at mid-life. For example, rod BE had oxide thicknesses which varied from 0.7 mil to approximately 4 mils in the 12 inch plane, where an apparent white corrosion product was seen during visual examination. One such area is shown in Figure 3-62. At several circumferential positions there was evidence that the oxide had partially spalled, accounting for the rough surface appearance discussed previously for rod BE. The two sections from rod BK also showed more extensive oxidation than the comparable MOL samples. Typical oxide films were 0.7-0.8 mil, with a maximum of 1.0 mil, as compared to typical thicknesses of 0.4-0.5 mil and a maximum of 0.6 mil on rods BO and NI at mid-life. It should be noted, however, that rod BK did not exhibit any of the anomalously thick or spalling oxide of the type seen on rod BE (See Section 3-3.3).

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The disproportionately thicker oxide on the high power rods at end-of-life indicates a higher corrosion rate during the 2200 EFPH's after mid-life than during the first 3700 EFPH of Core III operation. Further, the presence of significant quantities of adherent crud on the EOL rods, in contrast to little or no crud at MOL, suggests a change in the core environment, such as water chemistry, after mid-life with a resulting effect on crud deposition.

The first section of failed rod JX, at ~13 inches, showed surface features similar to those of rod BE at the 12 inch plane, including heavy oxidation of the outer clad surface. At one position the oxide had penetrated about 8 mils into the Zircaloy (See Figure 3-65). There was also clear evidence that some of the thick oxide had spalled, which accounts for the rough surface noted during visual examination and profilometry.

The 18 inch plane of rod JX also exhibited thick oxide on the outer surface but not to the same extent as at 13 inches. There was evidence of irregular reductions in clad wall thickness as a result of locally spalled oxide. The main feature of the microstructure in this plane was the extensive hydriding around most of the periphery, as indicated by numerous hydride precipitates and several areas of solid zirconium hydride. One of these solid hydride areas contained two small cracks, which originated at the external surface.

Figure 3-62 Abnormally Thick Oxide on Outer Surface of Rod BE, 12 Inches from the Bottom

Figure 3-63 Typical Oxide Film with Adherent Crud, 13.5 Inches from the Bottom of Rod BK

Figure 3-64 Adherent and Porous Crud and Oxide on Outer Surface of Rod BE, 17 Inches from the Bottom

Figure 3-65 Thick Oxide on Outer Surface of Rod JX,
13 Inches from the Bottom

The inner surface of the clad exhibited several mils of oxide, a characteristic of a defected rod which has operated for an extended period following failure. Examples of these conditions are shown in Figures 3-66, 3-67 and 3-68.

Although symptoms of a defected rod were clearly evident, neither the 13 inch nor 18 inch planes showed complete penetration of the clad. Therefore, an additional section was identified for characterization of the principal defected area just above the 13 inch plane. A significant portion of the rod near this plane had exhibited a rough surface with raised, scab-like patches and adjacent cavities during visual examination (See Figure 3-45). Examination of the sample after grinding to the 13.2 inch plane revealed severe oxidation in several locations. The photomicrograph in Figure 3-69 shows that the cladding was oxidized nearly all the way through in two circumferential positions. A 100X photomicrograph of one of these areas is presented in the same figure and illustrates the extremely thick, partially spalled oxide and the small amount of remaining clad (about 4 mils of the original 24 mils).

Further grinding and examination of the sample revealed more of the thick external oxide. There were also other symptoms of a defected rod, such as heavy hydriding and extensive oxidation of the internal surface. However, there was no direct metallographic evidence of complete clad penetration in this section or in any other section from this rod. These examinations indicate that the defected area of rod JX near the 13.2 inch plane must have been very small since incremental grinding with periodic inspection between 13.0 and 13.3 inches did not reveal complete clad penetration.

The 26.5 inch plane of rod JX was examined as representative of a non-defected area on this rod. It also exhibited heavy hydride precipitation and thick oxide on the internal surface of the clad. However, the outer corrosion oxide film was typically 0.5 mil thick with a maximum of 0.9 mil. There was also evidence of intermittent adherent crud. These observations suggest that there was no external accelerated oxidation in this region of the rod. They are also consistent with previous evidence from the 13 and 18 inch planes that coolant had entered the rod.

From the overall metallographic examination of sections of rod JX, it is concluded that the mode of failure was by accelerated oxidation originating on the outer surface of the cladding. Furthermore, this accelerated oxidation

NEG. JX-18-62

45°

100x

Figure 3-66 Extensive Hydriding, 18 Inches from the Bottom of Rod JX

Figure 3-67 Part of Solid Hydride Area Containing External Crack,
18 Inches from the Bottom of Rod JX

Figure 3-68 Oxide on Both Outer and Inner Surfaces of Rod JX, 18 Inches from the Bottom

Figure 3-69 Appearance of Severely Oxidized Clad on Failed Fuel Rod JX, 13.2 Inches from the Bottom

appeared to be related to an anomalous crud condition which developed after the mid-life shutdown and which had not been seen previously. A comparison of the surface and micro-structural features of rods BE and JX indicates that they both experienced abnormally rapid oxidation. The difference between the two was in degree -- with complete penetration of the cladding in rod JX but not in BE.

As in rod JX, the peak power section of failed rod PG examined as part of another program, also showed several areas of abnormally thick external oxide, a prominent rim of solid hydride near the outer surface, and an extensive oxide completely around the inner clad surface. However, it also exhibited several radial cracks in the cladding which apparently originated at the inner surface. This observation would suggest another possible failure mode for this rod and the three other rods which experienced a similar power history, i.e. low power in Core II, inserted into Core III at mid-life, and subjected to a power increase in excess of 10 kw/ft.

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The intermediate and low power rods (GM, FI and LS) generally showed external corrosion films 0.5 to 1.0 mil thick. These thicknesses are comparable to oxide films observed on MOL rods of similar power history. Figure 3-70 illustrates the end-of-life oxide film at the 18 inch plane of low power rod LS, where the oxide thickness is approximately 1.0 mil.

Table 3-17 summarizes all end-of-life corrosion film data, except for the rods which exhibited anomalous oxidation (rods BE and JX). It includes both maximum and typical values and shows the deduced Core II and Core III oxide thicknesses. The deduced Core II maximum thicknesses were based upon measurements of end-of-Core II samples with comparable power histories.[3]

The maximum corrosion films for all EOL rods outside the center 3 x 3 were similar: 0.9 to 1.2 mils. Thus, from Table 3-17, approximately 70 percent of the corrosion of rod BK occurred in Core III as compared with about 50 percent in rod GM and less than 35 percent in rods LS and FI. Similarly, about 40 to 45 percent of the corrosion in rods IM and PF took place during Core III. Since the fraction of Core III exposure time (~ 5800 MWD) to total time (~ 1500 MWD) was 0.4, it is concluded that the corrosion rates of the high and intermediate power rods were greater in Core III than in Core II. Conversely, the rates of oxide film buildup were slightly lower in Core III for the two low power rods (LS and FI).

A comparison of end-of-life and mid-life corrosion film thicknesses is given in Table 3-18, again excluding the

Figure 3-70 O. D. Oxide Film, 18 Inches from the Bottom of Rod LS

TABLE 3-17

SUMMARY OF EOL CORROSION MEASUREMENTS
AND INFERRED CORE III CORROSION

Rod No.	Axial Loc. From Bottom (in.)	Max. Oxide at EOL (mils)	Range of Typical Oxide EOL (mils)	Deduced Max. Core II Oxide (mils)	Inferred Max. Core III Oxide (mils)
IM	12.4	1.4	0.2 - 1.3	0.8	0.6
	18.9	1.5	0.3 - 1.3	0.8	0.7
PF	11.9	1.3	0.3 - 1.2	0.8	0.5
	17.9	1.3	0.2 - 1.0	0.8	0.5
BK	13.4	1.0	0.5 - 0.9	0.3	0.7
	17.9	1.0	0.4 - 0.9	0.3	0.7
GM	11.9	1.0	0.2 - 0.9	0.5	0.5
	17.1	0.9	0.2 - 0.5	0.5	0.4
LS	11.9	1.0	0.4 - 0.9	0.8	0.2
	17.9	1.1	0.5 - 1.0	0.8	0.3
FI	11.9	1.2	0.6 - 1.1	0.8	0.4
	17.9	1.2	0.3 - 1.0	0.8	0.4

TABLE 3-18

COMPARISON OF END-OF-LIFE AND MID-LIFE

CORROSION FILM THICKNESS

Relative Power in Core III	EOL or MOL	Rod No.	Max. Oxide Thickness, Mils, at	
			11-13 in.	17-20 in.
Mod.. High (13-15 kw/ft)	EOL	IM	1.4	1.5
		PF	1.3	1.3
	MOL	LZ	1.2	1.4
High (15-18 kw/ft)	EOL	BK	1.0	1.0
	MOL	BO	0.6	0.6
		NI	0.6	0.5
Intermediate (11-13 kw/ft)	EOL	GM	1.0	0.9
	MOL	GL	0.6	0.6
		FS	0.9	0.8
Low (9-11 kw/ft)	EOL	FI	1.2	1.2
		LS	1.0	1.1
	MOL	MQ	1.1	1.2

data for rods BE and JX. Note that the maximum corrosion films at EOL were not appreciably higher than those of comparable power samples examined at MOL, except for high power rod BK (~ 1.0 mil vs. 0.6 mil for rods BO and NI). These results suggest that, (as expected) for all but the highest power rods, the incremental corrosion in the final 2200 EFPH was very small compared to that which occurred during the previous 13,300 EFPH.

With the exception of rods BE and JX, hydride precipitation was not significantly different in EOL samples than that observed at mid-life. Again, the hydrides were typically circumferentially or randomly oriented. Subsequent analyses of ring samples of cladding confirmed a favorably low hydrogen absorption during exposure in Core III. As shown in Table 3-19, the average end-of-life hydrogen levels were generally in the range of 60 to 116 ppm, as compared with 66 to 111 ppm at mid life. These similarities in hydrogen levels suggest that the incremental hydrogen uptake from MOL to EOL was negligible. The exceptions were a sample from rod BE, where locally heavy corrosion of the outer surface had occurred, and a sample from failed rod JX, which of course showed extremely severe oxidation and hydriding and, therefore, an expectedly high (653 ppm) hydrogen concentration.

2. Clad-Fuel Interface

All metallographic samples from end-of-life non-failed rods exhibited an oxide layer on the inner surface of the cladding. Typically this oxide was 0.2 to 0.5 mil thick. In many cases, it appeared to be detached from the clad and partially bonded to the fuel (Figure 3-71). There were also numerous instances of complete gap closure with apparent chemical bonding across the fuel-to-clad interface, as illustrated in Figure 3-72. This condition was more prevalent on end-of-life samples than at mid-life or end-of-Core II; furthermore, it was observed on nearly all rods, regardless of power history.

In spite of extensive fuel-clad bonding and apparent gap closure, none of the samples in the MOL or EOL examinations showed any evidence of inner surface reaction zones of the type seen on rod RR, which had been discharged after ~ 1700 EFPH in Core III, (See Section 3-1.3). In addition, there was no evidence of localized clad attack or other adverse effects on the cladding.

3. Fuel Structure

All sections of EOL fuel rods displayed the usual patterns of radial and circumferential cracks for fuel which had operated for long periods at power levels above 10 kw/ft.

TABLE 3-19

SAXTON END-OF-LIFE CLAD HYDROGEN ANALYSES

Rod Number	Sample Location (Inches from Bottom)	Average H ₂ (1) Concentration (ppm)	Range of H ₂ Concentration (ppm)
FI	12.1	60	57-62
LS	12.1	64	59-68
GM	12.1	38	32-43
BE	12.1	361 ⁽²⁾	140-910
BK	13.4	100	62-138
JX (Failed)	26.6	653	627-678
IM	19.1	116	92-139
PF	18.1	95	94-95

(1) Average of two determinations

(2) Average of four determinations

Figure 3-71 Partially Detached Oxide Layer at Fuel-Clad Interface of Rod BK

Figure 3-72 Fuel-Clad Bonding, 17.0 Inches from the Bottom of Rod FI

As shown in Figure 3-73, the normal radial cracks were observed to be virtually closed near the periphery of the fuel. The crack closure appeared to be progressive with burnup and power, i.e., more pronounced in highest burnup rods IM and PF and in high power rods BE and BK. Examination of microstructures confirmed that the apparent volume of fuel cracks and fuel-to-clad gap were even less than seen on the mid-life samples.

The patterns of grain growth and homogenization in high power rods BE and BK were consistent with their power history, and their microstructures were similar to those of mid-life rods BO, NI and RD. None of the EOL samples exhibited a central void, although several (e.g., BE and PF) showed clusters of relatively large spheroidal pores near the thermal center of the fuel. Columnar grain growth was clearly evident in rods BE, BK and JX and to a lesser extent in rods IM and PF; there was no columnar grain growth in the three lower power rods. As expected, all sections exhibited equiaxed grain growth. On the five rods which experienced peak powers above ~ 15 kw/ft, equiaxed growth was observed from the edge of the columnar grains outward to approximately 75 percent of the fuel radius. The low and intermediate power rods (FI, LS and GM) showed equiaxed growth up to ~ 65 percent of the radius. Associated with the areas of both columnar and equiaxed grain growth were many small metallic-appearing particles, presumably fission product precipitates.

The EOL samples showed patterns of gas bubble distribution similar to those of the mid-life fuel. The major features included:

- a. Large pores associated with PuO_2 particles in the peripheral area of the fuel.
- b. A relatively large volume of gas bubbles immediately outside the region of equiaxed grain growth.
- c. Apparent redistribution of small gas bubbles to grain boundaries in the regions of equiaxed and columnar grain growth.
- d. As noted previously, large spheroidal pores near the thermal center of high power rods.
- e. No identifiable as-fabricated porosity in any metallographic section.

Examples of these microstructural features are shown in Figures 3-74, 3-75 and 3-76, which are montages of photomicrographs representing the following three power

NEG. HC 30906

~10X

Figure 3-73 Macrograph of Transverse Section of Rod IM,
12.25 Inches from the Bottom

Figure 3-74 Edge to Center Composite of Fuel
Microstructure - Rod BE, 0°
Traverse, 12 Inches from Bottom

Figure 3-75 Edge to Center Composite of Fuel Microstructure - Rod PF, 315° Traverse, 12 Inches from Bottom

NEG. FI-12-40

AS-POLISHED

NEG. FI-12-47

NEG. FI-12-6

ETCHED

NEG. FI-12-13

(150X)

Figure 3-76 Edge to Center Composite
of Fuel Microstructure -
Rod FI, 0° Traverse, 12
Inches from Bottom

history types:

<u>Rod No.</u>	<u>Relative Power in Core II</u>	<u>Relative Power in Core III</u>
BE	Lowest	Highest
PF	Highest	High
FI	Highest	Lowest

In general, the fuel microstructures of failed rod JX were similar to those of BE, which experienced a comparable power history. An unusual structural feature seen on the samples from rod JX was an anomalously large grain size at the fuel periphery. However, there was no clear evidence of fuel oxidation, washout or other significant microstructural changes due to operation in the failed condition.

In general, the end-of-life fuel structures were not significantly different from those observed at mid-life or end of Core II for rods of comparable power history. The only changes noted were progressive closure of radial cracks near the periphery and closing of the fuel-clad gap.

4. Autoradiography

Autoradiographs of four metallographic sections were prepared to determine the degree of PuO_2 homogenization and segregation of fission products. These samples represented the full range of power histories.

As seen in Figure 3-77, the alpha autoradiograph of the 18 inch plane of rod BK (high power) showed areas of discrete alpha emission and generally higher alpha activity near the periphery due to greater plutonium isotope generation in this region. It also showed homogenization of the center area of the fuel out to ~65 percent of the radius, which is generally consistent with grain growth observations.

Similar patterns were evident in other sections, with the size of the homogenized region in the center decreasing at lower power levels.

The beta-gamma autoradiograph of rod BK (Figure 3-78) showed typical features for a rod which had experienced columnar grain growth, i.e., a central region of high activity surrounded by one of markedly lower activity. This pattern is believed to be the result of fission product segregation in areas of large thermal gradients.

**Figure 3-77 Alpha Autoradiograph of Rod BK, 18 Inches from Bottom
(White Areas Represent High Alpha Activity)**

Figure 3-78 Beta-Gamma Autoradiograph of Rod BK, 18 Inches from Bottom (Dark Spots Represent High Beta-Gamma Activity)

As with the fuel microstructures, the general features of the EOL autoradiographs were comparable to those from rods examined at end of Core II and at mid-life where power histories were similar, e.g., rod BK at EOL and rod BO at mid-life.

c. Fluence Measurements

Fast fluence analyses of selected EOL clad samples were made in the same manner as for MOL samples (See Section 3-2.4c). The resulting Mn-54 activities and their corresponding fast neutron fluences are given in Table 3-20. Since all of these samples were taken from close to the peak burnup location of each rod, the range of fluence is relatively small -- from about 3.1 to 4.3×10^{21} n/cm² (E > 1 Mev). As expected, the fluences were generally higher than for comparable rods at MOL, with the highest values for the two lead burnup rods (IM and PF), which remained in the center 3 x 3 subassembly throughout Core III. However, the incremental fluences between MOL and EOL were greatest for the intermediate power rod GM (increase of ~45 percent) and lowest for rods IM and PF.

d. Burnup Measurements

Each of the eight EOL rods were sampled for burnup and isotopic compositions in the same manner as for the MOL rods. The results are given in Table 3-21 and show that, as expected, the highest measured burnups were in the two rods irradiated in the center 3 x 3, rods IM and PF. The peak burnups of the remaining rods ranged from 40,000 to 43,200 MWD/MTM. Ten radial drill samples from near the center of rod IM were also analyzed for burnup and isotopic composition. The results of these analyses and a discussion of all burnup data reduction and comparisons of measurements with predictions are presented in Reference 4.

e. Tensile Testing

Tensile tests were performed on eight end-of-life samples at 675°F, utilizing the same equipment and conditions as used for mid-life material. The results of these tests are given in Table 3-22. A comparison of EOL results with those from MOL (Table 3-12) and end of Core II (Table 4-15 of Reference 3) indicates generally higher yield and ultimate strengths for the EOL material, which is reasonable in view of the lower linear heat rating near EOL. The exceptions were the two samples from the highest power rods BE and BK, which had ultimate strengths of about 62,000 psi as compared with ~70,000 to 95,000 psi for other EOL samples. This difference is consistent with their higher power, thus higher clad temperatures, throughout Core III. On the other hand, the uniform elongations of all EOL samples were in the range of 1.3 to 2.6 percent, nearly the same as for MOL material but significantly below those of Core II samples. Similarly, the EOL and MOL total elongations

TABLE 3-20
FLUENCE RESULTS⁽¹⁾

Rod Identity	Sample Midpoint Location, Inches From Bottom of Fuel Stack	Measured Mn-54 Activity, dpm/mg Fe x 10 ⁷	Fast Neutron Fluence, E > 1 Mev n/cm ² x 10 ²¹
FI	16.13	3.85 ⁽²⁾	3.1
LS	16.13	3.81 ⁽²⁾	3.1
GM	16.13	5.01 ⁽²⁾	4.1
BE	16.13	4.82 ⁽²⁾	3.9
BK	16.13	4.24 ⁽³⁾	4.2
JX	15.13	4.24 ⁽³⁾	4.2
IM	17.13	4.28 ⁽³⁾	4.2
PF	16.13	4.39 ⁽³⁾	4.3

(1) End of irradiation for these rods was May 1, 1972.

(2) Mn-54 activities on January 15, 1973.

(3) Mn-54 activities on April 10, 1973.

TABLE E-21
CORE III END-OF-LIFE BURNUP DATA

Fuel Rod No.	Sample Midpoint Location, in. (1)	Measured Burnups, MWD/MTM H.E. (2) Method Nd-148 Method		% Difference (3)	U-234	U-235	U-236	U-238	Fu-238	Pu-239	Pu-240	Pu-241	Pu-242	Pu-239/U-238 (10-2)	Nd-148/U-238 (10-4)	Date of Analysis
FI	16.5	41,650	39,980	+ 4.2	0.005	0.403	0.063	99.527	0.712	52.125	34.274	10.117	2.772	2.319	7.286	1/3/73
LS	16.5	42,580	42,850	- 0.4	0.005	0.415	0.063	99.517	0.737	50.388	35.471	10.379	3.028	2.182	7.795	1/2/73
GM	16.5	39,560	40,740	- 2.6	0.005	0.428	0.061	99.506	0.656	53.761	33.761	9.885	2.534	2.393	7.403	1/5/73
IM	17.0	29,970	50,860	-41.1	0.005	0.360	0.073	99.562	1.020	43.847	38.898	11.979	4.256	1.157	8.973	5/14/73
PF	16.5	49,870	50,950	- 2.1	0.005	0.357	0.071	99.567	0.984	44.492	38.477	11.936	4.111	1.852	9.281	5/15/73
BE	16.5	41,680	41,490	+ 0.5	0.005	0.411	0.060	99.524	0.665	50.660	36.259	9.704	2.708	2.201	7.543	10/25/73 (4)
BK	16.5	43,880	43,260	+ 1.4	0.005	0.399	0.065	99.531	0.703	48.352	37.506	10.327	3.112	2.657	7.368	4/16/73
JX	16.8	42,870	43,180	- 0.7	0.005	0.401	0.064	99.531	0.734	49.237	36.978	10.215	2.936	2.088	7.856	10/26/73 (4)(5)

(1) Distance from bottom end of rod

(2) Heavy Element

(3) $\frac{\text{Measured (by H.E.)} - \text{Measured (by Nd)}}{\text{Measured (by Nd)}}$

(4) Date of reanalysis

(5) Plutonium isotopic abundances determined on 7-11-73.

TABLE 3-22

675°F TENSILE TEST DATA - END-OF-LIFE SAMPLES

Rod Identity	Axial Location (In. from Bottom)	Est. Fluence, ⁽¹⁾ (10 ²¹ n/cm ²)	Pre-EOL Kw/ft ⁽²⁾	0.2% Yield Strength (10 ³ psi)	Ultimate Strength (10 ³ psi)	Uniform Elong. (%)	Total Elong. (%)
BE	18-24	3.5	9.0	45.1	62.0	2.2	3.4
BK	19-25	3.5	10.8	39.1	61.8	1.3	5.5
IM	29-35	2.3	6.3	69.7	86.0	2.6	7.0
PF	5-11	4.0	9.5	51.9	87.5	2.3	5.8
GM	29-35	2.2	5.5	67.6	79.3	2.7	14.3
LS	25-31	2.4	5.6	57.1	85.7	2.3	5.3
FI	18-24	2.8	6.4	73.4	80.1	1.9	3.9
FI	29-35	2.2	4.6	49.3	77.1	1.8	4.3

(1) Estimated fluence at center of sample, based on measured fluence near center of rod.

(2) Linear heat rating at center of sample prior to EOL shutdown.

were not greatly different for samples of comparable power history, except in the highest power rods. (Samples from MOL rod B0 had elongations of ~8 to 10 percent, as compared with 3 to 6 percent for two EOL samples.). These results suggest that uniaxial ductility had reached or was close to a saturation level sometime before Core III mid-life. The highly variable values of total elongation and other anomalies are likely related to the complex power history of the loose lattice rods between MOL and EOL, especially during the last two months, when the reactor operated at 65 to 70 percent of full power. They could also be associated with the unusual adherent crud and thick oxide which formed on many of the loose lattice rods after Core III mid-life.

A typical fracture area from rod IM, is shown in Figure 3-79. This figure helps to illustrate the extent of the axial and diametral strain in EOL tensile samples.

f. Burst Testing

Burst testing of eight EOL samples was also performed at 657°F, mainly to provide a direct comparison with MOL burst data. As indicated in Table 3-23, the yield and burst (failure) strengths of the EOL samples were generally higher than those of Core II (Table 4-16 of Reference 3) or MOL rods (Table 3-13). Furthermore, for cladding of comparable irradiation history, the EOL samples showed somewhat lower circumferential failure strains but never less than 2 percent. These lower strains at EOL are consistent with the significantly lower power levels (thus lower clad temperatures) during the final two months of Core III operation. The relatively high ductility and low burst strength of the specimen from rod BK are probably due to its higher time-averaged clad temperature as compared with other samples, and suggests a similar trend to that of the MOL burst test results, i.e., high ductility and lower strength for samples which experienced high power before MOL.

The appearance of a typical EOL sample (from rod IS) in the area of the burst opening is illustrated in Figure 3-80. In contrast, a non-typical sample (from rod GM) is shown in Figure 3-81.

The overall results of the MOL and EOL mechanical testing illustrated the expected strengthening and reduction in ductility of the loose lattice cladding as a result of Core III irradiation. Although the cladding elongation and burst strain values were lower than those of end-of-Core II samples, they were sufficiently high to indicate a generally ductile behavior.

P4867

4X

Figure 3-79 Fracture Area of Tensile Sample from Rod IM

TABLE 3-23

675°F BURST TEST DATA - END-OF-LIFE SAMPLES

Rod Identity	Axial Location (In. from Bottom)	Est. Fluence ⁽¹⁾ (10^{21} n/cm ²)	Pre-EGL Kw/ $\bar{t}$ t(2)	0.2% Yield Stress (10^3 psi)	Failure Stress, (10^3 psi)	Failure Strain (%)	Wall Thickness Reduction (%)
BE	25.0-33.0	2.7	7.1	92.4	94.6	2.5	27
BK	3.0-11.0	3.8	10.8	59.9	62.1	11.2	33
IM	3.0-11.0	3.8	9.4	72.4	81.0	4.7	12
PF	26.0-34.3	2.8	6.6	72.4	72.7	6.6	15
GM	3.0-11.0	3.5	7.3	72.6	84.5	7.6	20
GM	18.0-26.0	3.5	7.6	66.5	69.1	2.6	2
LS	3.0-11.0	2.8	6.0	75.0	84.5	3.8	16
FI	3.0-11.0	2.8	5.7	70.5	79.0	2.4	15

(1) Estimated fluence at center of sample, based on measured fluence near center of rod.

(2) Linear heat rating at center of sample prior to EOL shutdown.

P4827

4X

Figure 3-80 Typical Burst Opening in Sample from Rod LS

P4824

4X

Figure 3-81 Non-Typical Burst Sample, from Rod GM

3-3.5. Summary of Performance Inferred from Examination of EOL Rods

Examination of nonfailed mixed oxide fuel rods representing a wide range of power histories revealed good overall performance at peak burnups of 40,000 to 51,000 MWD/MTM. Progressive changes from mid-life were observed in rod length, fuel microstructure, fuel-clad bonding, and mechanical properties of cladding. However, these changes were consistent with increased irradiation time and had no apparent effect on fuel performance. On the other hand, profilometer scans, fission gas collection and hydrogen analysis showed results similar to those observed at mid-life on rods of comparable power history.

The defects which developed in loose lattice rods after mid-life were limited to rods near the upper end of the power spectrum and were associated with a grossly accelerated oxidation and an anomalous crud condition not seen previously on any Saxton fuel rods. In addition, metallographic evidence indicated a second possible failure mode in loose lattice rods inserted at mid-life and related to large power increases (Ref. page 3-69); these rods were not part of the EOL sampling plan. The rods defected by corrosion do not appear to be indicative of an inherent power, burnup or other performance limitation in Zircaloy-clad mixed oxide fuel.

SECTION 4

CONCLUSIONS

The examination of mixed oxide ($\text{PuO}_2\text{-UO}_2$) fuel rods after extended irradiation in the loose lattice region of Saxton Core III leads to the following general conclusions:

- a. The overall performance of plutonium fuel irradiated to peak burnups of 40,000 to 51,000 MWD/MTM was satisfactory.
- b. Defects which developed in certain high power rods between Core III mid-life and end-of-life did not appear to be related to any burnup, power or other inherent performance limit of mixed oxide fuel.
- c. The rods showed progressive changes in dimensions, fission gas release, clad oxidation, fuel microstructure and mechanical properties consistent with increased burnup and higher power operation. However, with the exception of accelerated oxidation on defected rods, the changes had no apparent adverse effects on performance.

Specific conclusions resulting from the post-irradiation evaluation of these rods are as follows:

- a. All non-failed rods were dimensionally stable, with a maximum of 0.11 percent increase in rod length and between 1.5 mils increase and 1.3 mils decrease in diameter as a result of further irradiation in Core III. As with mixed oxide rods irradiated in Core II, the extended burnup rods showed creepdown in their intermediate and higher power regions during Core II and Core III of about one to two mils relative to the low power (cold) ends.
- b. The fuel columns remained relatively stable throughout Core III, with no observed gaps in excess of 100 mils.
- c. The highest fractional release of fission gases was slightly higher at the end-of-Core III than at the end-of-Core II (37 vs 32 percent), which is consistent with the power histories of the rods involved.
- d. Clad corrosion rates were higher in Core III than in Core II for high and intermediate power rods. The maximum non-accelerated corrosion film thickness of 1.5 mils on the highest burnup rods was consistent with expectations.

- e. Hydrogen absorption by the cladding in Core III was not a problem, with only slightly higher concentrations observed at end-of-life than measured in lead rod cladding at end-of-Core II.
- f. Microstructural evidence showed progressive closure of the fuel-clad gap at high burnup and progressively more fuel-clad bonding. These phenomena, however, had no adverse effect on dimensional stability or on overall fuel performance.
- g. Cladding from extended burnup rods exhibited widely variable mechanical properties but generally had higher strength and lower ductility than cladding from Core II. The variability is probably the result of large differences in power history for the rods which were sampled. Despite the generally lower tensile and burst elongations, the cladding retained adequate ductility.

SECTION 5

REFERENCES

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APPENDIX A

TABLE A-1

SAXTON CORE III FISSION GAS ISOTOPIC DATA

Rod Identity	Removal Date	Isotopic Composition, a/o							
		Krypton				Xenon			
		83	84	85	86	131	132	134	136
RR	5/70	16.5	30.0	5.7	47.7	12.5	20.7	27.7	39.0
LZ	3/71(MOL)	16.6	30.6	6.1	46.7	12.1	20.9	27.5	39.5
LZ(1)	3/71(MOL)	16.3	30.6	6.0	47.1	12.0	20.9	27.6	39.5
BO	3/71(MOL)	16.7	30.0	6.3	47.0	13.0	20.4	27.8	38.8
BO(1)	3/71(MOL)	16.8	29.8	6.2	47.2	13.0	20.3	27.9	38.8
NJ	3/71(MOL)	16.9	30.1	6.1	46.9	12.8	20.9	28.0	38.3
FS	3/71(MOL)	16.6	30.4	6.1	46.9	12.8	20.9	28.0	38.2
GL	3/71(MOL)	16.9	30.1	5.8	47.2	12.8	21.1	28.2	37.8
RD	3/71(MOL)	16.8	30.1	6.1	47.0	12.8	20.5	28.0	38.6
MQ	3/71(MOL)	16.6	30.7	5.9	46.8	12.4	21.4	28.0	38.2
IM	5/72(EOL)	16.3	31.0	5.8	46.9	12.0	21.3	27.4	39.1
PF	5/72(EOL)	16.6	30.9	5.7	46.8	12.2	21.0	27.7	38.9
BE	5/72(EOL)	16.9	30.5	6.0	46.6	12.8	21.0	27.8	38.2
BK	5/72(EOL)	16.9	30.4	6.0	46.7	12.6	21.1	27.4	38.7
GM	5/72(EOL)	16.8	30.6	5.8	46.9	12.4	21.4	28.0	38.0
LS	5/72(EOL)	16.3	31.2	5.5	47.0	12.1	21.6	27.8	38.3
FI	5/72(EOL)	16.5	31.1	5.7	46.7	12.3	21.5	28.0	38.0

(1) Backup analysis

APPENDIX B

APPENDIX B

GENERAL PROCEDURE FOR THE PREPARATION OF METALLOGRAPHIC SPECIMENS FOR SAXTON PLUTONIUM PROGRAM

MOUNTING

1. Specimens were placed in pre-drilled and hardened Bakelite premolds, 1-1/4 inch diameter x 1-1/2 inch long.
2. Epoxy resin (Hysol #6020 or #2038 resin and #3404 hardener, 9:1 by weight) was added to fill cavity of mount.
3. Mounts were degassed in vacuum chamber (with alternate evacuation and pressurization to atmosphere).
4. When degassing was complete, mounts were removed from chamber and allowed to harden at room temperature for $\geq$ 16 hours.

GRINDING

1. Specimens were ground in successively finer stages, using 120 to 600 grit Sic papers with H_2O lubricant.
2. Specimens were cleaned ultrasonically between each grinding stage.

POLISHING

1. Rough polishing was done on Metcloth with diamond paste abrasive, 15 to 1 micron, depending on condition.
2. Fine polishing was done on Microcloth or Texmet cloth with Al_2O_3 abrasive, 0.05 micron. In some cases vibratory polishing was utilized to achieve a fine polish.
3. Specimens were cleaned ultrasonically between each polishing stage.

ETCHING

1. Fuel was etched with H_2O_2 (30%) and Conc. H_2SO_4 , 3:1 to 9:1 by volume; ~1 minute immersion.
2. Clad was etched with Conc. HCl and Conc. HNO_3 , 5:1 by volume, ~1 minute swab.
3. Specimens were rinsed with H_2O , then with alcohol and dried with warm air.

APPENDIX C

TABLE C-1

IDENTIFICATION AND CORE LOCATIONS OF
LOOSE LATTICE ASSEMBLIES

<u>Assembly No. (1)</u>	<u>Core Location (2)</u>
17-8	C2
17-2	D2
17-3	E2
17-4	D3
17-5	C4
17-6	D4
17-9	E4

(1) Last three digits of assembly serial number

(2) Location in core indicated in Figure C-1

ASSEMBLY LOCATIONS IN CORE

A1	A2	A3	A4	A5	A6	A7	A8	A9
B1								B9
C1								C9
D1							D8	D9
E1							E8	
F1							F8	
G1							G8	
H1			H4	H5	H6	H7	H8	
J1	J2	J3	J4	ROD LOCATIONS IN ASSEMBLIES				

Figure C-1. Nomenclature for Rod and Assembly Locations in Saxton Plutonium Program

APPENDIX D

APPENDIX D

DETERMINATION OF TOTAL VOLUME OF GAS RELEASED

The total volume of gas released from each punctured rod is determined twice. The initial value is obtained from pressure change measurements made at the hot cells immediately after puncture of the rod. The gas is then Toepler pumped into two sample vials. One vial is sent to the mass spectrometer where gas composition and gas pressure measurements are made, while the second vial is stored for possible future use. The pressure data from the sample vial is used to back calculate the total volume of gas released from the rod. This value is then compared with the initial value determined at the hot cell. In all but two cases, the sample vial results show less than 5 percent deviation from the hot cell data. These cases are discussed in following paragraphs.

The total volume of gas determinations based on the hot cell pressure measurements is judged to be the most accurate measurement of gas release. With the exceptions of MOL rod B0 and EOL rod GM, the values for total volume of gas released as reported in Tables 3-7 and 3-16 are based on hot cell pressure measurements. The values reported for rods B0 and GM are based on pressure measurements made on sample vials at the mass spectrometer for the following reasons:

a. Rod B0

The mass spectrometer results for gas composition, as reported in Table 3-7, show significant quantities of N_2 and O_2 . Air in-leakage occurring after the initial puncture/pressure measurement event is suggested by a higher value for total volume of gas based on the sample vial pressure measurement (146 STP cc) than was calculated from the hot cell pressure measurement (138 STP cc). It is therefore necessary to use the total volume of gas, as determined by pressure measurements on the sample vial, in conjunction with the mass spectrometer gas composition data to calculate the total volume of fission gas released from rod B0. Use of the hot cell volume determination (when air was not present) would result in an erroneously low fractional gas release (35 percent vs 37 percent).

b. Rod GM

As reported in Quarterly Progress Report WCAP-3385-34, some problems were encountered in the determination of the total volume of gas released from EOL rod GM. There was a major discrepancy in the total volume of gas as determined at the hot cells vs later measurements on the sample vial at the mass spectrometer. Subsequent pressure measurements and gas composition determinations on the backup vial have confirmed the results from the primary sample. An overall evaluation of the hot cell puncture and gas collection data and the mass spectrometry results on the primary and backup vials leads to the following conclusions:

1. The pressure recorded immediately after rod puncture was in error and the collection data suggests that all gas may not have been collected.
2. The mass spectrometry data shows no air in-leakage. Pressure measurements taken on sample vials at the mass spectrometer provide the best "measure" of total volume of gas collected from rod GM.
3. The total volume of gas value based on the sample vial pressure measurements (as listed in Table 3-16) should be qualified to recognize that all gas may not have been collected. Therefore, the total volume of gas released from EOL rod GM was at least 73.3 STP cc.

FRACTIONAL GAS RELEASE

Measured fractional gas release as reported in WCAP-3385-31 for the MOL rods and WCAP-3385-34 for the EOL rods are based on nominal fuel densities and fuel volumes. The MOL data considered measured rod average burnups while the EOL data were based on calculated rod average burnups. All fractional gas release values as reported in Tables 3-7 and 3-16 of this report have been recalculated. Individual rod densities (based on measured preirradiation fuel stack heights and weights) individual rod fuel volumes, best estimate rod average burnups normalized to measured Nd-148 results, and measured total volumes of gas as determined at the hot cells, have been used in these calculations. These final fractional release values vary slightly from previously reported values. The maximum difference is observed on rod BK where the measured release has changed from 33 to 36 percent.